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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**HIGH-SPEED NUMERIC FUNCTION GENERATOR USING
PIECEWISE QUADRATIC APPROXIMATIONS**

by

Njuguna Macaria

September 2007

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**HIGH-SPEED NUMERIC FUNCTION GENERATOR USING QUADRATIC
APPROXIMATIONS**

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The CORDIC algorithm is an accurate way to compute the value of a function like $\sin(x)$, for a given value of x . However, it is iterative and slow. In this thesis, we show that a wide class of arithmetic functions can be realized on the SRC-6, a reconfigurable computer, using polynomial approximations. The function is realized by partitioning its domain into segments and then approximating the function in each segment by a quadratic polynomial. This is not an iterative approach, and so it is faster than the CORDIC algorithm

Two approximation methods are implemented. In one method, non-uniform segments are used. Here, larger segments can be used where the function is close to quadratic, while highly non-quadratic regions require smaller segments. This approach minimizes the number of segments. In the other method, uniform segments are used. Although more segments are needed than in the non-uniform method, the circuit is simpler.

We show that accuracies of up to 33 bits are possible. A pipelined circuit was built on the SRC-6 in two's complement and floating point. We also show an efficient algorithm for segmenting the function, which is faster than previous methods.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASIC	Application Specific Integrated Circuit
BDD	Binary Decision Diagram
BRAM	Block Random Access Memory
BUA	Basic Unit of Accuracy
CORDIC	Coordinate Rotation Digital Computer
CPU	Central Processing Unit
CSA	Carry Save Adder
CLAH	Carry Look Ahead Adder
DEL	Direct Execution Logic
DLD	Dense Logic Device
DSP	Digital Signal Processing
ECS	Engineering Capture System
EVBDD	Edge-Valued Binary Decision Diagram
FPGA	Field Programmable Gate Array
HDL	Hardware Description Language
I/O	Input / Output
IEEE	Institute of Electrical and Electronics Engineers
ISE	Integrated Software Environment
ITE	If, Then, Else
LSB	Least Significant Bit
LUT	Look-Up Table
MAP [®]	Multi-adaptive Processor
MHz	Megahertz
MSB	Most Significant Bit
MS	Microsoft
NFG	Numeric Function Generator
NPS	Naval Postgraduate School
OBM	On-Board Memory
PC	Personal Computer
RAM	Random Access Memory

ROM	Read Only Memory
SRC	Seymour R Cray
USN	United States Navy
Verilog	A C-Based HDL
VHDL	VHSIC Hardware Description Language
VHSIC	Very High Speed Integrated Circuit

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EXECUTIVE SUMMARY

This thesis focuses on the high-speed implementation of arithmetic functions, such as $\sin(\pi x)$, $\ln(x)$ and 2^x . Meteorological computations, scientific calculations and graphics are applications that require fast mathematical computation.

The CORDIC algorithm and Taylor series expansion are methods used to compute trigonometric functions. The CORDIC algorithm is hardware efficient, precise, but iterative in design and therefore slow.

In this thesis, we investigate a way to speed up mathematical computations by using piecewise quadratic approximations built on reconfigurable hardware. The function is realized by partitioning its domain into segments and then approximating the function in each segment by a quadratic polynomial. This is not an iterative approach, and so it is faster than the CORDIC algorithm

The reconfigurable hardware used is the SRC-6E that is designed by SRC Computers in Colorado Springs, Colorado.

The objectives were to:

- Find an efficient algorithm to segment any numeric function using piecewise quadratic approximations.
- Find an accurate segmentation (accurate when evaluated using the approximation polynomial) to any numeric function given an accuracy constraint in terms of number of bits.
- Design pipelined hardware for the Numeric Function Generator (NFG) with a small pipeline depth (compared to what is currently available).
- Design NFG to operate at 100MHz or faster on the FPGA.

Segmentation is a preliminary step to provide a memory file that contains the number of segments for the numeric function, and each segment's coefficients needed to compute the approximation polynomial.

MATLAB is used to segment any function over a defined interval. The MATLAB program needs to know the function, interval, desired accuracy and the number of discrete points in the interval. The MATLAB built-in function, *Polyfit*, was used to compute the coefficients of the approximation polynomial, but analysis showed that the approximation computed using this method did not efficiently segment the function. *Polyfit* is computationally fast, but results in an inefficiently segmented function.

The *Remez* algorithm is used to efficiently segment the numeric function. The *Remez* algorithm evenly distributes the approximation error on each segment, but is computationally intensive and slow. Several methods were investigated to speed up the algorithm. The best method to speed up the program, involved a hybrid of three methods.

- Segment width estimation that requires the third derivative of the numeric function and the accuracy desired by the user.
- Search algorithm similar to a binary search
- Single stepping through points and testing to determine if the accuracy has been met.

The program computes an estimated segment width and a metric is used to determine the quality of the estimation. If the metric indicates the estimation quality is poor, then the program will use the search algorithm to get closer to the optimum width. In the final step, the program single steps through the points and tests each approximation to determine when the accuracy has been met. When the segmentation of the function is complete, the optimum segment width and the associated coefficients are saved in a memory file for use in the NFG.

The segmentation algorithm sped up the program tremendously. If the domain is divided into over a million points, the original program would take at least one million tests to segment a function. In each test, the program computes the coefficients and tests the polynomial against the numeric function to see if the accuracy is met. When the speed up algorithm is used, the program requires much less than 0.1% of the number of tests than without the speed up. Table 1 shows the results when 15 functions were tested.

The interval is shown in the second column, the speed up is shown in percentage format in the third column and the last column shows the number of segments. The percentage is computed as: $\frac{\# \text{ of tests} \times 100}{1,000,000}$.

Epsilon = 0.0000000596 = $2^{-24.0}$. N = 1000000			
Function	Interval	%Of tests	# of Segments
2^x	[0,1]	0.00910	35
$1/x$	[1,2]	0.01020	50
\sqrt{x}	[1,2]	0.00750	24
$1/\sqrt{x}$	[1,2]	0.00720	36
$\log_2(x)$	[1,2]	0.00900	44
$\log(x)$	[1,2]	0.00780	39
$\sin(\pi x)$	[0,1/2]	0.01990	58
$\cos(\pi x)$	[0,1/2]	0.01740	58
$\tan(\pi x)$	[0,1/4]	0.01240	58
$\sqrt{-\log(x)}$	[1/512,1/4]	0.04070	163
$\tan(\pi x)^{\dots}$	[0,1/4]	0.02180	79
$-(x \log_2(x))$	[1/256,1-1/256]	0.04710	183
$1/(1+\exp(-x))$	[0,1]	0.00920	20
$(1/\sqrt{2 \cdot p})$	[0, $\sqrt{2}$]	0.01670	45
$\sin(\exp(x))$	[0,2]	0.07810	265

Table 1. Speed-up in computation time for 15 functions (expressed as a percentage of the time needed when the domain is divided into 1,000,000 points) for $\varepsilon = 2^{-24}$.

The NFG circuit consists of three multipliers, one 3-input adder, a segment indexing method and the memory that contains the approximation polynomials' coefficients for each segment.

Figure 1 is a block diagram that shows an overview of the NFG circuit.

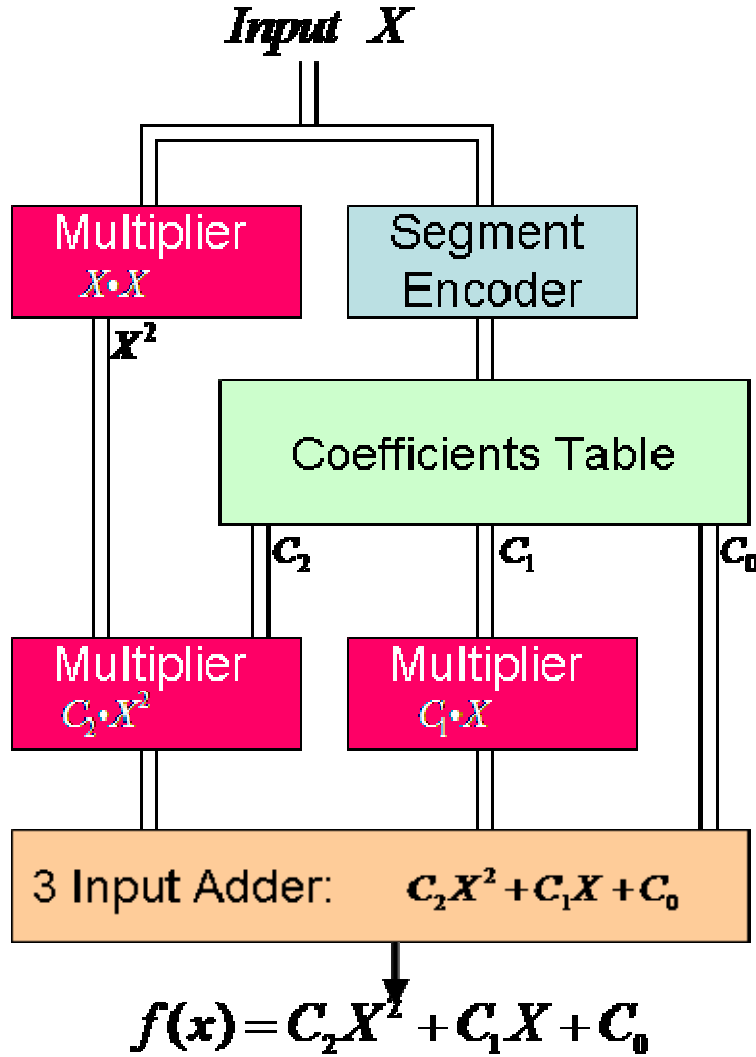


Figure 1. Numeric function generator (NFG) architecture.

Two approximation methods are implemented. In one method, non-uniform segments are used. Here, larger segments can be used where the function is close to quadratic, while highly non-quadratic regions require smaller segments. This approach minimizes the number of segments. In the other method, uniform segments are used. Although more segments are needed than in the non-uniform method, the circuit is simpler.

We show that accuracies of up to 33 bits are possible. A pipelined circuit was built on the SRC-6 in two's complement and floating point. The floating point implementation is easier to program via the interface that SRC provides. A

<subroutine>.mc file is a C-like file that is compiled into the hardware that resides on the FPGAs in the SRC Multi-Adaptive Programming (MAP) board.

Using fixed point implementation produces a shorter pipeline depth (approximately 30% of the floating point pipeline depth), but requires more effort by the programmer to ensure the bits are aligned correctly. In fixed point implementation, the bits are truncated instead of rounded. This introduces errors in the intermediate computations that propagate to the final answer.

The best solution to this problem is to build a user macro multiplier that takes care of the rounding and ensures the bits are aligned in the intermediate results of the polynomial computation.

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I. INTRODUCTION

A. PROBLEM STATEMENT AND PURPOSE

High-speed numeric computation has many applications including digital signal processing, graphics rendering, meteorological modeling, etc. These applications require numeric calculations to be computed quickly. In addition, the hardware may be required to compute large amounts of data or streaming data, which means long periods of time, may be expended performing the one type of computation. Personal computers are general purpose and not specifically designed for numeric calculations alone; instead they provide the best compromise between speed and flexibility.

The CORDIC algorithm can be very precise, but it has the disadvantage of being iterative and slow; the operations can take hundreds to thousands of clock cycles. Each iteration in the CORDIC algorithm provides increased accuracy at the output [4].

It would be beneficial to have specialized and fast hardware for high speed numeric calculations. Conventional methods for computing numeric functions include the CORDIC algorithm [2], [3], [4]. The problem is that specialized hardware is inflexible to computing different numeric functions as well as to changes in requirements or software updates. However, specialized hardware is fast.

A very fast method for numeric calculations is a look-up table [5], i.e. for every possible input, store the desired output of the numeric function. The disadvantage of this approach is that a large amount of memory is needed.

Field programmable devices have the advantage that one can quickly design, test and replace hardware functionality. This is compared to traditional methods, whereby a prototype is designed and simulated in software, prototyped on a prototyping board, and then sent to a manufacturer. This is expensive and time consuming, especially if there are changes required.

FPGA technology has improved to the point that a large amount of logic is available. If we have a few divergent needs that may require particularly heavy-computation that can best be solved by specialized hardware, we can use the FPGA devices to implement a specialized hardware design. Once the task has been completed,

the hardware can be reconfigured for other uses. The NFG we will discuss uses this principle on the SRC-6 computer system.

Lee, Wayne, Villasenor and Cheung [6], used a cascade of AND and OR gates to calculate segment addresses in a non-uniform segmentation implementation for hardware function evaluation. This circuit is useful for a limited class of functions. Sasao, Butler and Riedel [5] present a universal circuit that can cater to a wider class of functions.

Sasao, Butler and Riedel [5] have shown that elementary and non-elementary numeric functions can be computed quickly and accurately using a piecewise linear approximation method. This method provides some advantages over the memory method and the CORDIC algorithm. Less memory is required than a look-up table because the numeric function is segmented and the coefficients of the piecewise linear approximation are stored vice storing every possible input value and its corresponding output. The other advantage is that the accuracy can be determined at the outset and therefore is faster than the CORDIC algorithm; especially at higher accuracy when the CORDIC must go through several iterations to attain the desired accuracy. One more advantage to this approach is that it allows for one hardware design, with the memory contents being changed to handle different numeric functions [1].

This thesis investigates a piecewise quadratic implementation. The quadratic implementation requires fewer segments than the linear implementation to compute the same numeric functions to the same accuracy. This also means that the memory required is less than that required to implement a piecewise linear approximation NFG.

B. IMPLEMENTATION OVERVIEW

Figure 1 shows of the hardware required to build the NFG using quadratic approximation. The NFG architecture requires three multipliers. Each requires significant logic and causes significant delay.

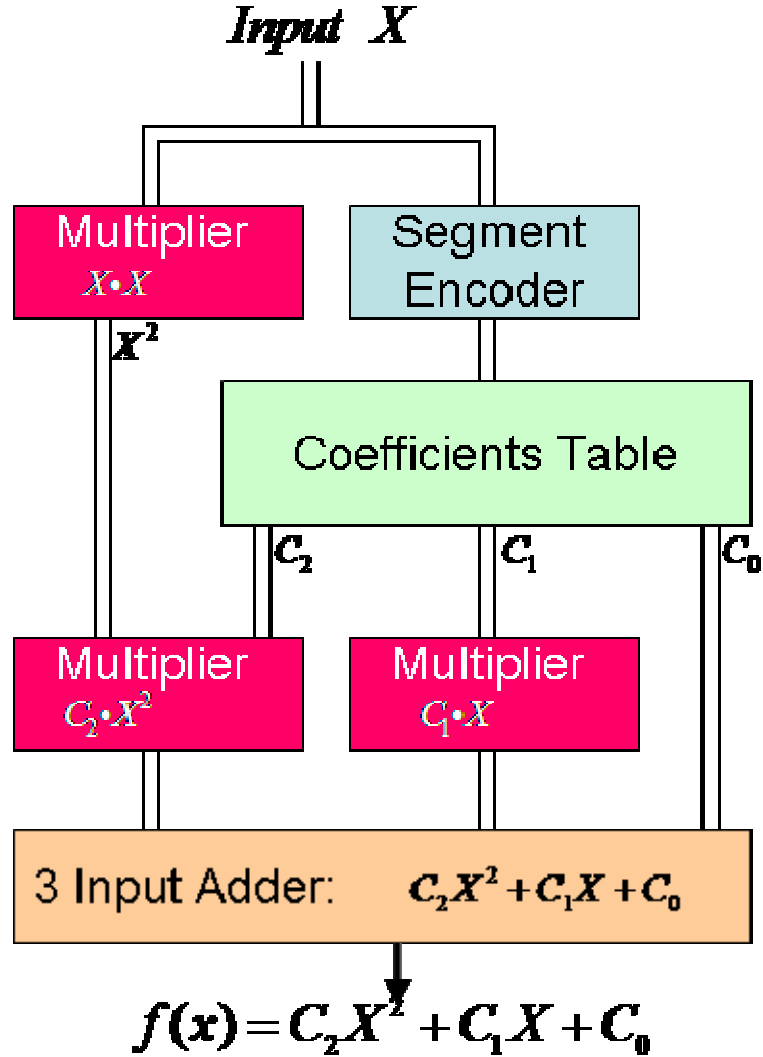


Figure 1. Numeric function generator (NFG) architecture.

Table 1 shows the suite of functions used to test and design the NFG. Unlike logic or software design, there is no set of benchmarks. The specific functions have been chosen because they have appeared in previous papers on this subject [1], [5], [8], [9],[11], [12], [15].

#	Function f(x)	Interval	
		x	f(x)
1	2^x	$[0,1]$	$[1,2]$
2	$1/x$	$[1,2]$	$[1/2,1]$
3	\sqrt{x}	$[1,2]$	$[0,\sqrt{2}]$
4	$1/\sqrt{x}$	$[1,2]$	$[1/\sqrt{2},1]$
5	$\log_2(x)$	$[1,2]$	$[0,1]$
6	$\ln(x)$	$[1,2]$	$[0,\ln 2]$
7	$\sin(\pi x)$	$[0,1/2]$	$[0,1]$
8	$\cos(\pi x)$	$[0,1/2]$	$[0,1]$
9	$\tan(\pi x)$	$[0,1/4]$	$[0,1]$
10	$\sqrt{-\ln(x)}$	$[1/512,1/4]$	$[\sqrt{-\ln(1/4)},\sqrt{-\ln(1/512)}]$
11	$\tan^2(\pi x)+1$	$[0,1/4]$	$[1,2]$
12	$-(x \log_2 x + (1-x) \log_2(1-x))$	$[1/256,1-1/256]$	$[0,1]$
13	$\frac{1}{1+e^{-x}}$	$[0,1]$	$[1/2,\frac{1}{1+e^{-1}}]$
14	$\frac{1}{\sqrt{2\pi}}e^{\frac{-x^2}{2}}$	$[0,\sqrt{2}]$	$[\frac{1}{\sqrt{2\pi}},\frac{1}{\sqrt{2\pi}e^1}]$
15	$\sin(e^x)$	$[0,2]$	$[1,-1]$

Table 1. Suite of numeric functions and their domains.

C. THESIS ORGANIZATION

This thesis is organized into six chapters. Chapter I is the introduction, Chapter II covers the segmentation of numeric functions and the methods used for computing the approximation of the functions; this includes the discussion on how the coefficients were computed and how the memory files were used in the NFG. These programs were designed in MATLAB [7]. In Chapter III, the circuit description design is covered. Chapter IV introduces the SRC computer architecture. The experimental results are discussed in Chapter V. The summary and suggested future work is discussed in Chapter VI.

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II. FUNCTION APPROXIMATION

The NFG approximates the realized function by polynomial. In a typical realization, many polynomials are used. A segment is a sub-domain in the interval of approximation where one polynomial is used to approximate the function. In this thesis quadratic polynomials are used. The benefit of using a polynomial approximation is that only one hardware design is required to realize a multitude of functions. The only change required to the hardware is to change the specific endpoints of the segmentation of the functions to be realized and the associated coefficients. The segmentation endpoint and coefficients are generated in MATLAB and are stored in a memory file. Segmentation is described in detail below.

The realized functions are approximated and the output of the hardware is only as accurate as the user-defined precision. The approximation error is ε . The exact function is evaluated for various values in the domain. The polynomial that is used to approximate the function is evaluated for the same values in the domain. The difference between these two results is the approximation error ε . The approximation error ε is the constraint used to keep the approximation in check.

The approximation error ε , directly impacts how many segments are required and therefore dictates how much memory is used to store the coefficients. Small values require many segments.

A. QUADRATIC VS LINEAR

Nagayama, Sasao and Butler [8] showed that using quadratic approximations in the NFG requires an average of only 4% of the memory required when using linear approximations. This gives the motivation to pursue quadratic approximation following the work on linear approximation that was performed by Mack [1].

In Table 2, the number of segments required for different accuracies is tabulated for both quadratic approximation and linear approximation. A column is also included that shows the ratio of quadratic to linear segments required.

Function	$\varepsilon = 2^{-17}$		$\varepsilon = 2^{-24}$		$\varepsilon = 2^{-33}$	
	Segments Quad/Lin	%	Segments Quad/Lin	%	Segments Quad/Lin	%
2^x	7/75	9.33	35/849	4.12	278/19008	1.46
$1/x$	10/75	13.33	50/849	5.89	400/18996	2.11
\sqrt{x}	5/35	14.29	24/388	6.19	189/8729	2.17
$1/\sqrt{x}$	8/50	16.00	36/565	6.37	288/12684	2.27
$\log_2(x)$	9/76	11.84	44/853	5.16	351/19097	1.84
$\ln(x)$	8/63	12.70	39/710	5.49	311/15927	1.95
$\sin(\pi x)$	12/109	11.01	58/1227	4.73	461/27361	1.68
$\cos(\pi x)$	12/109	11.01	58/1227	4.73	459/27361	1.68
$\tan(\pi x)$	12/73	16.44	58/822	7.06	459/18371	2.50
$\sqrt{-\ln(x)}$	33/207	15.94	163/2356	6.92	1312/47188	2.78
$\tan^2(\pi x) + 1$	16/152	10.53	79/1721	4.59	631/38087	1.65
$-(x \log_2 x + (1-x) \log_2(1-x))$	37/314	11.78	183/3556	5.15	1459/76334	1.91
$\frac{1}{1+e^{-x}}$	4/20	20.00	20/226	8.85	158/5087	3.11
$\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$	9/53	16.98	45/595	7.56	357/13312	2.68
$\sin(e^x)$	54/449	11.80	265/5099	5.20	2121/101065	2.10

Table 2. Segmentation required for linear and quadratic approximations.

To calculate the memory required for a single segment, one needs to take into account that memory for linear approximations only requires two quantities (slope and intercept) and memory for quadratic approximation requires three quantities. That is a 50% increase in memory requirements for a single segment when compared to linear.

However, the sheer difference in number of segments required for quadratic vice linear, more than counterbalances for the increase in memory requirements

Table 2 shows that quadratic approximations can cover more functions with fewer segments than linear approximations and on average, quadratic approximations take up only 4% of the memory required to represent the same function when using linear approximations [8].

B. SEGMENTATION

To evaluate a numeric function using polynomial approximation, we need to segment the domain of the numeric function such that each segment has one set of coefficients that evaluate to the polynomial approximation of the given numeric function. The polynomial approximation needs to satisfy the user defined ε such that any value in the domain that is evaluated using the polynomial will produce an output $f(x)$ that has an error no greater than ε in magnitude. The segmentation is performed in MATLAB routines.

Segmentation can be performed using either uniform or non-uniform segments. The coefficients of the approximation polynomial can be computed using *Polyfit* [7], which is a built-in MATLAB function or the *Chebyshev* and the *Remez* [13] algorithm which is a user function. We will discuss these approaches in more detail.

1. Uniform and Non-Uniform Segmentation

There are two general methods used in approximating a function; uniform and non-uniform segmentation. Different functions behave differently when segmented using uniform or non-uniform segmentation. Non-uniform segmentation allows the user to take advantage of functions that have both rapidly changing and non-rapidly changing sections. When functions have sections of high curvature, non-uniform segmentation can create smaller segments to ensure the polynomial approximation does not exceed ε . The more quadratic or linear the function is, the better the polynomial approximation can fit a quadratic polynomial to it. As a result, segments are longer in regions where the function

is linear or quadratic. The goal is to achieve the fewest segments possible and yet achieve the approximation error specified by the user. Figure 2 shows the non-uniform segmentation of $\sqrt{-\ln(x)}$ using $\varepsilon = 2^{-16}$ (accurate to 16 binary bits). This function illustrates the advantage of non-uniform segmentation. The smaller segments are located at the beginning of the domain and the larger segments are at the end.

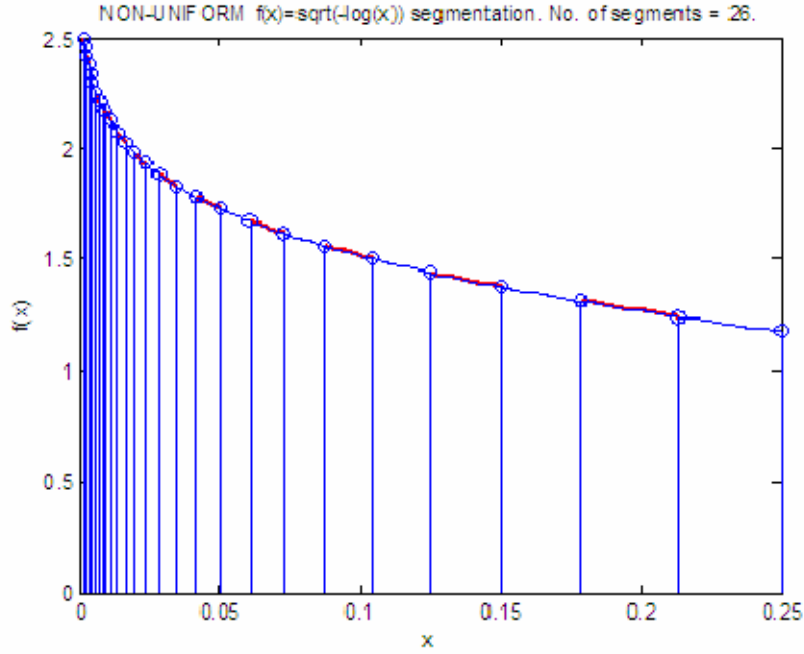


Figure 2. Quadratic segmentation of $\sqrt{-\ln(x)}$ shows the difference in the size of segments due to curvature of the function.

As mentioned above, the error associated with this segmentation should not exceed $\varepsilon = 2^{-16}$. Figure 3 shows the error across the interval of approximation when non-uniform segmentation is used. For all but the last segment, the maximum absolute error is the same (about $2^{-16.011}$). As shown in Figure 3, the error does not exceed ε anywhere. Note that the error in the last (right most) segment is much less than in all other segments. This is because the last segment is truncated by the boundary of the domain interval before the algorithm has a chance to maximize the size of the segment.

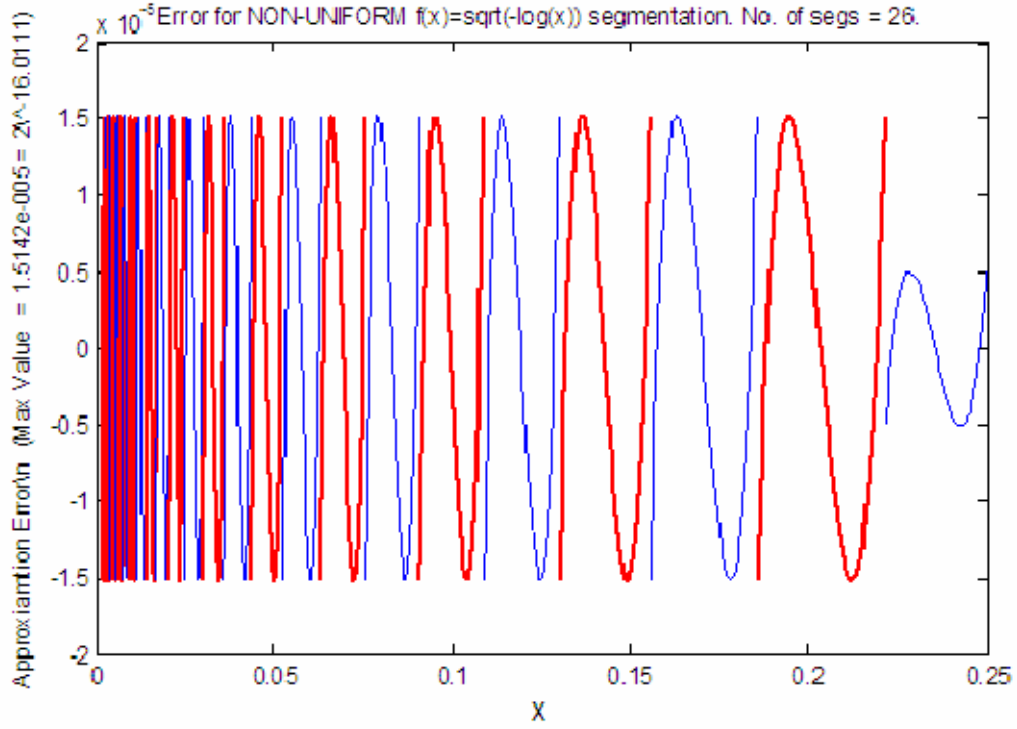


Figure 3. Segment error of $\sqrt{-\ln(x)}$ when $\varepsilon = 2^{-16}$.

Figure 4, shows the approximation error in the case of this same function when uniform segmentation is applied¹. To achieve uniform segmentation within the same approximation error specification i.e. 2^{-16} , we are required to use the width of the narrowest segment which in this case is the very first segment.

¹ Because a large number of segments are required, the line width occupies the whole of the figure, making it appear completely solid.

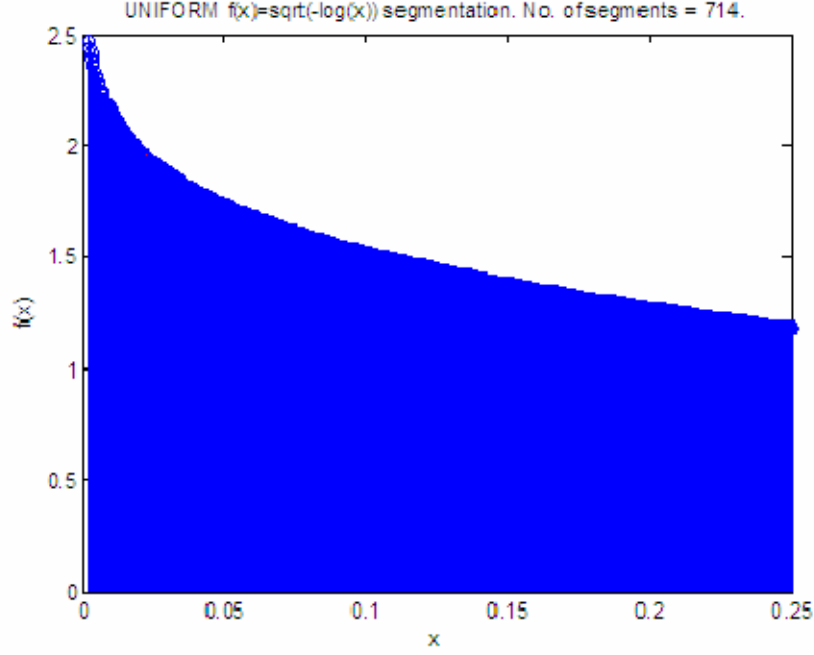


Figure 4. Quadratic uniform segmentation for $\sqrt{-\ln(x)}$ when limited when $\varepsilon = 2^{-16}$.

The error function for a uniform segmentation looks different from that of the non-uniform segmentation. The error for uniform segmentation is maximum i.e. ε is attained in the most limiting segment. However, when looking at the other segments the error does not reach ε . Therefore a tapered effect is observed. To best demonstrate this effect, we shall use a less “dramatic” function than $\sqrt{-\ln(x)}$. Instead $\cos(\pi x)$ is used in Figure 5 and Figure 6 to show the difference in the error between the uniform and non-uniform segmentation.

Below in Figure 5, the error is tapered showing that the earlier segments don’t take full advantage of the entire segment because they have been limited by the smallest segment, located at the end of the domain for the $\cos(\pi x)$ function.

In Figure 6 however, you can see that non-uniform segmentation has taken full advantage of all the space and has fewer segments to represent the same function. This is the advantage of the non-uniform segmentation over uniform segmentation.

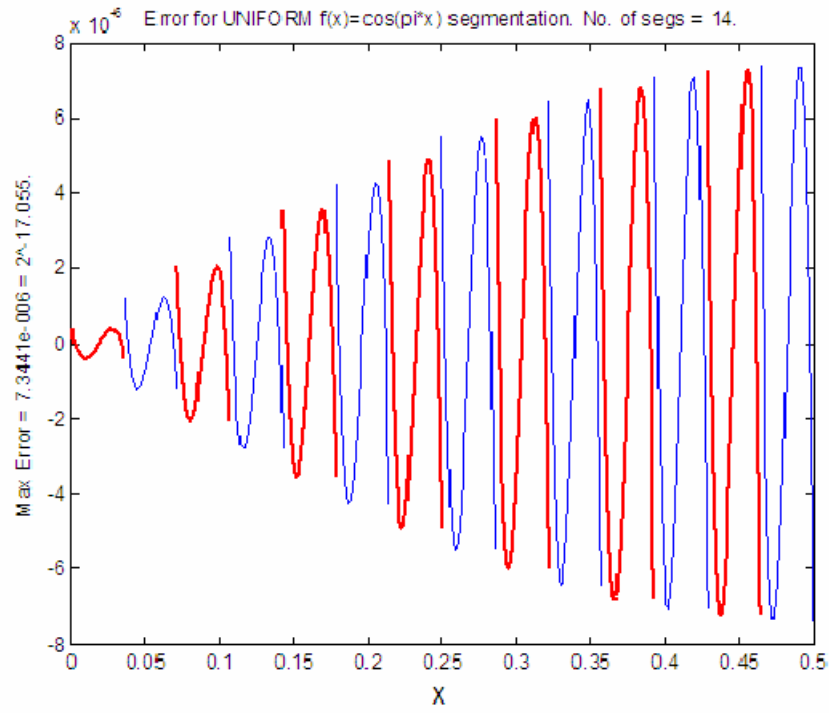


Figure 5. Uniform segmentation error for $\cos(\pi x)$ when limited by $\varepsilon = 2^{-17}$.

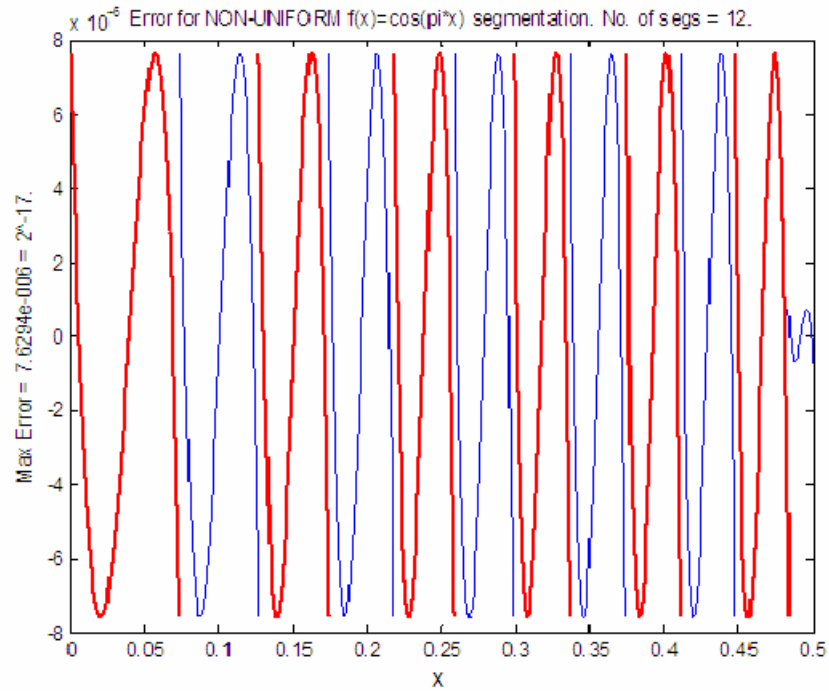


Figure 6. Error for non-uniform segmentation for $\cos(\pi x)$ when limited by $\varepsilon = 2^{-17}$.

In the segmentation of a numeric function, a user interface was designed in a MATLAB program to get the user's choices. The user interface allows the user to select which function he/she would like to segment and allows the user to select the number of points (to subdivide the domain), ε , and whether uniform or non-uniform segmentation is used.

If the user selects non-uniform segmentation, the interface looks like that shown in Figure 7.

```
*****

      QUADRATIC APPROXIMATION OF A FUNCTION USING CHEBYCHEV
      AND REMEZ ALGORITHM

*****

Functions to be compared          Interval
1.  2^x                          [0,1]
2.  1/x                          [1,2]
3.  sqrt(x)                      [1,2]
4.  1/sqrt(x)                    [1,2]
5.  log2(x)                      [1,2]
6.  log(x) = ln(x)              [1,2]
7.  sin(pi*x)                   [0,1/2]
8.  cos(pi*x)                   [0,1/2]
9.  tan(pi*x)                   [0,1/4]
10. sqrt(-log(x)) = sqrt(-ln(x)) [1/256,1/4]
11. tan(pi*x)^2 + 1             [0,1/4]
12. -(x*log2(x) + (1-x)*log2(1-x)) [1/256,1-1/256]
13. 1/(1+exp(-x)) = 1/(1+e^(-x)) [0,1]
14. (1/sqrt(2*pi))*exp(-x^2/2)   [0,sqrt(2)]
15. sin(exp(x))                 [0,2]

*****

Input the Function, func[sqrt(-1*log(x))]:
(1)Non-uniform or (2)Uniform Segmentation or (3)Both [1]:
Input the Desired Error, epsilon[2^-33]: 2^-16
Input the no. of pts the fct is to be evaluated, N[1000000]:

*****
```

Figure 7. Quadratic approximation user-interface when non-uniform segmentation has been used.

If the user selects non-uniform segmentation, the user interface allows the user to select whether he/she wants to specify ε or if they would like to use a fixed number of segments instead. The new user interface looks like that shown in Figure 8.

```
*****

      QUADRATIC APPROXIMATION OF A FUNCTION USING CHEBYCHEV
      AND REMEZ ALGORITHM

*****

Functions to be compared          Interval
1.  2^x                          [0,1]
2.  1/x                          [1,2]
3.  sqrt(x)                      [1,2]
4.  1/sqrt(x)                    [1,2]
5.  log2(x)                      [1,2]
6.  log(x) = ln(x)              [1,2]
7.  sin(pi*x)                   [0,1/2]
8.  cos(pi*x)                   [0,1/2]
9.  tan(pi*x)                    [0,1/4]
10. sqrt(-log(x)) = sqrt(-ln(x)) [1/256,1/4]
11. tan(pi*x)^2 + 1              [0,1/4]
12. -(x*log2(x) + (1-x)*log2(1-x)) [1/256,1-1/256]
13. 1/(1+exp(-x)) = 1/(1+e^(-x)) [0,1]
14. (1/sqrt(2*pi))*exp(-x^2/2)   [0,sqrt(2)]
15. sin(exp(x))                  [0,2]
*****

Input the Function, func[sqrt(-1*log(x))]: 8
(1)Non-uniform or (2)Uniform Segmentation or (3)Both [1]: 2
Would you like to constrain (1)Number of Segments or (2)Error [1]:
Input the number of Desired Segments[20]: 50
Input the no. of pts the fct is to be evaluated, N[1000000]: |
```

Figure 8. Quadratic approximation user-interface when uniform segmentation has been specified.

a. Summary of Advantages and Disadvantages of Uniform and Non-Uniform Segmentation

Table 3 shows a summary of the advantages and disadvantages between uniform and non-uniform segmentation.

	Advantages	Disadvantages
Uniform Segmentation	<ul style="list-style-type: none"> • No need for segment index encoder • Less complex hardware 	<ul style="list-style-type: none"> • High curvature functions require many segments (wastes memory)
Non-Uniform Segmentation	<ul style="list-style-type: none"> • High curvature functions with segments that are as wide as possible (Saves on memory) 	<ul style="list-style-type: none"> • Requires segment index encoder • More complex design

Table 3. Summary of Advantages and Disadvantages of Uniform and Non-uniform Segmentation.

2. Segment Coefficients Using Polyfit and the Remez Algorithm

To obtain the coefficients of a segment when segmenting any function, several different algorithms may be used. In [5], Sasao et al use the Douglas-Peucker algorithm [10] for segmenting and providing linear approximations to the functions. However this algorithm does not yield an optimum segmentation [11].

The initial work in this thesis used the *Polyfit* [7] function, available in MATLAB, to find the coefficients. *Polyfit* is computationally efficient and has been optimized for MATLAB. It requires a set of data points that represent the function that the user intends to best fit a polynomial of order n . In this thesis, we are working with quadratic functions and therefore use $n = 2$. *Polyfit* finds the coefficients to the approximating polynomial in a least squares sense [7] and returns a row vector with the coefficients of the polynomial. Least squares approximations minimize the average error on the interval selected. However, the worst-case error can be large. That is, it yields an average error that satisfies the constraint given, i.e. ε , but the worst-case errors may still exceed the constraint.

In analyzing the approximation polynomials produced from the coefficients provided by the *Polyfit* function, the graphs showing the error over each segment had the largest error at the begin and end points of the segment as can be seen in Figure 9 below.

This graph shows the weakness in using least squares approximation methods like that used by *Polyfit*. Our goal is to reduce the number of segments for the given function in order to restrain the maximum error to no greater than ε . Therefore, *Polyfit* was abandoned and instead the *Remez* algorithm [13] was used.

The *Remez* algorithm uses a method of approximation that minimizes the worst-case error. It belongs to the set of least maximum approximations (*minimax* approximations). The program ensures that there was no point in the interval where the error found by evaluating the difference between the approximation polynomial and the real function was greater than the constraint given.

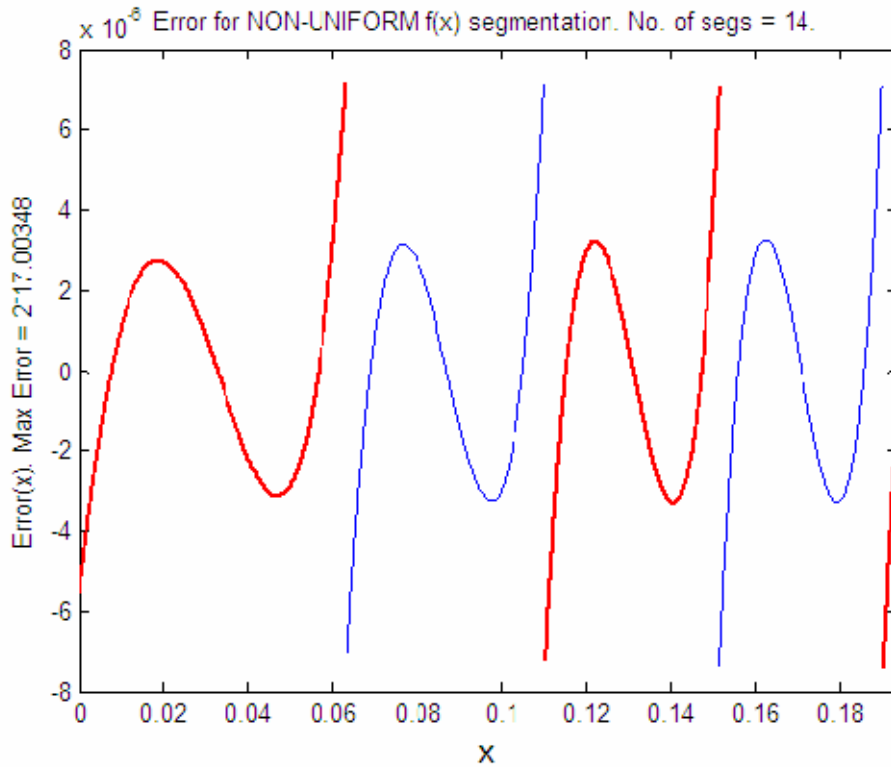


Figure 9. Quadratic non-uniform segmentation approximation error using *Polyfit*.

The advantage of the *Remez* algorithm is to evenly distribute the error over the segment so that the maximum error is constrained by ε . This can be clearly observed by

comparing Figure 9 and Figure 10. The function, $\cos(\pi x)$ with $\varepsilon = 2^{-17}$, was used in both cases. Notice *Polyfit* needed 14 segments while *Remez* only required 12 segments. Both figures display only the first 4 segments. The difference is readily noticeable. Thus the *Remez* covers a larger portion of the domain in the four segments than *Polyfit*. As a result, it tends to reduce the number of segments. In the *Remez* implementation, the 4th segment extends right past 0.21 in the x domain, while *Polyfit* barely makes it to 1.9.

The *Remez* algorithm attempts to achieve the *minimax* degree- n polynomial approximation of the given function on a defined interval. In the program that was used for this thesis, the interval is iteratively revised and the *Remez* algorithm is repeatedly called until a degree-2 polynomial approximation that satisfies the constraint is achieved. The process is constrained by ε , and the interval is increased or decreased until the optimum segment endpoint lies between the current point and the next point on the domain interval.

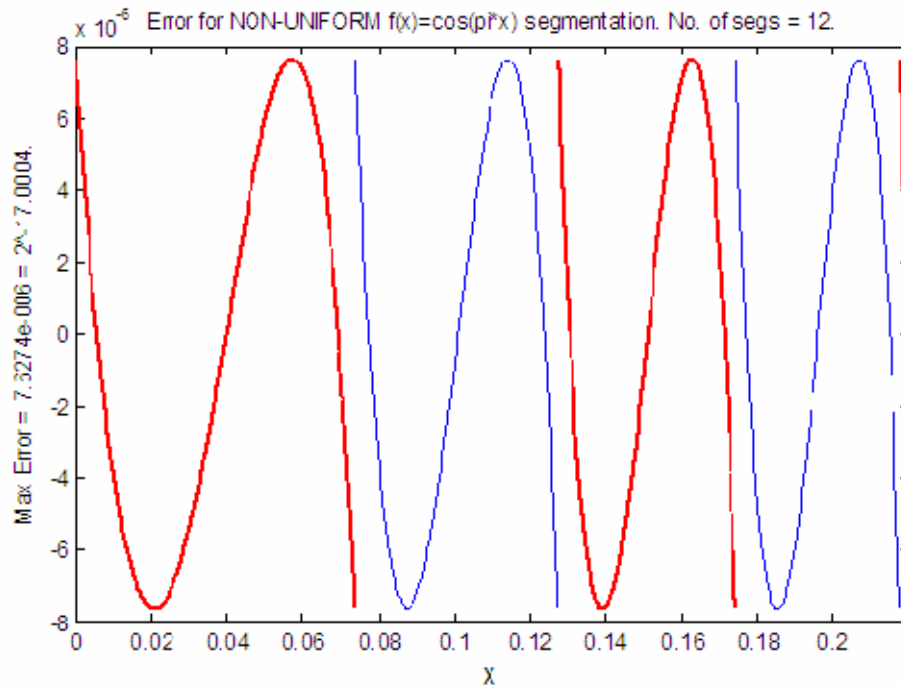


Figure 10. Quadratic non-uniform segmentation approximation error using *Remez*. (Only the first four segments are shown).

The *Remez* algorithm requires much more computational time and effort than the *Polyfit* function (which is already optimized for MATLAB). In general, for an f with an interval $[a, b]$, there are several polynomials, but only one polynomial p^* is the *minimax* degree- n approximation. This approximation will have at least $n+2$ points, as described in inequality (0.1) that evaluate to yield an error that will be maximum magnitude and will alternate in sign.

$$a \leq x_0 < x_1 < \dots < x_{n+1} < b \quad (0.1)$$

The begin point and end point of the interval are included. In the case of quadratic approximations, a degree-2 polynomial can expect at least 4 points where the error will be maximum and will alternate in sign, as seen in Figure 10. The *Remez* algorithm is iterative and requires an estimate of the point where the error is maximum. The *Chebyshev* approximation is better than most other approximation algorithms in obtaining a polynomial close to the *minimax* polynomial p^* . When compared to *Taylor Series*, *Legrendre*, *Chebyshev* provides a better estimate in most cases. For this reason, *Chebyshev* approximation is used to provide a set of starting points in the *Remez* algorithm in this thesis. The previous discussion is described in more detail in [13].

The function *ChebyRemez* in Appendix B was written to implement the *Remez* algorithm with an initial set of points where the error is maximum. Using *Remez* slowed down the program written to compute the coefficients; especially when higher accuracy was desired or in general, when the x domain interval was assigned more points; N . To neutralize this effect, different algorithms were investigated to speed up the program. These are discussed further in the section three below.

3. Algorithms Investigated to Speed-Up the Segmentation

In the program proposed by Sasao, Butler and Riedel [5], the domain was divided into points and segmentation was determined by brute force, i.e. point by point to determine the required size of the segment. To attain high accuracy, the domain needs to

be subdivided into hundreds of thousands and even millions of points. This results in slow execution. We investigate ways to speed up the segmentation.

a. *Brute Force*

The lower value of the domain is established as the begin point. The program steps through each point computing the *minimax* degree-2 polynomial approximation of the function. When evaluating any segment, (even two consecutive points), the program creates 1000 points between the given begin point and the end point. This ensures enough points for the program to locate the points in the segment where the maximum and minimum error is achieved, as described above. The coefficients required are then computed and next, the approximated polynomial is used to evaluate all the points in the current segment. These values are compared with the actual values from computing the real function. The maximum error is determined. If the error is smaller than ε , the program steps one point to the right and repeats the process. Eventually, the polynomial approximation will produce an approximation where the maximum error exceeds ε . At this point the program steps back one step and records the end point of the segment. For a typical segmentation with $N=1,000,000$, this program takes much time. N is defined as the number of points on the entire interval of the domain, i.e. number of points on the interval $[a, b]$.

b. *Binary Search*

Binary search is really a two step process:

1. Locate: A point close to the optimum point is determined.
2. Pinpoint: Use brute force to move up to the optimum point.

In step 1, given a function f , and an interval $[a, b]$, starting on the left at a , the lower value of the domain is established as the begin point and the end point is set to b . This is the entire domain interval over which the program computes the *minimax* degree-2 polynomial approximation. Given the constraint, ε , the program tests the error of the approximation and if the error is greater than the constraint, the program divides

the interval into two equal parts and decreases the proposed interval. Figure 11 shows a graphic representation of the first 4 iterations. These iterations are part of step 1; Locate.

The optimum is endpoint of the first segment is labeled x_0 . Figure 11 shows the first iteration, interval $[a, b]$ is tested to determine if it is a good segment size. Since it is too large, the interval is divided into 2. The new interval is $[a, 1^{st} \text{ proposed } x_0]$. The process is repeated and the approximation of this new proposed segment is tested against the constraint. This is an iterative process that decreases the width of the segment. The next proposed segment is $[a, 2^{nd} \text{ proposed } x_0]$ as shown in Figure 11. Again the segment is tested. If the constraint is not met, the segment is decreased by $1/2$.

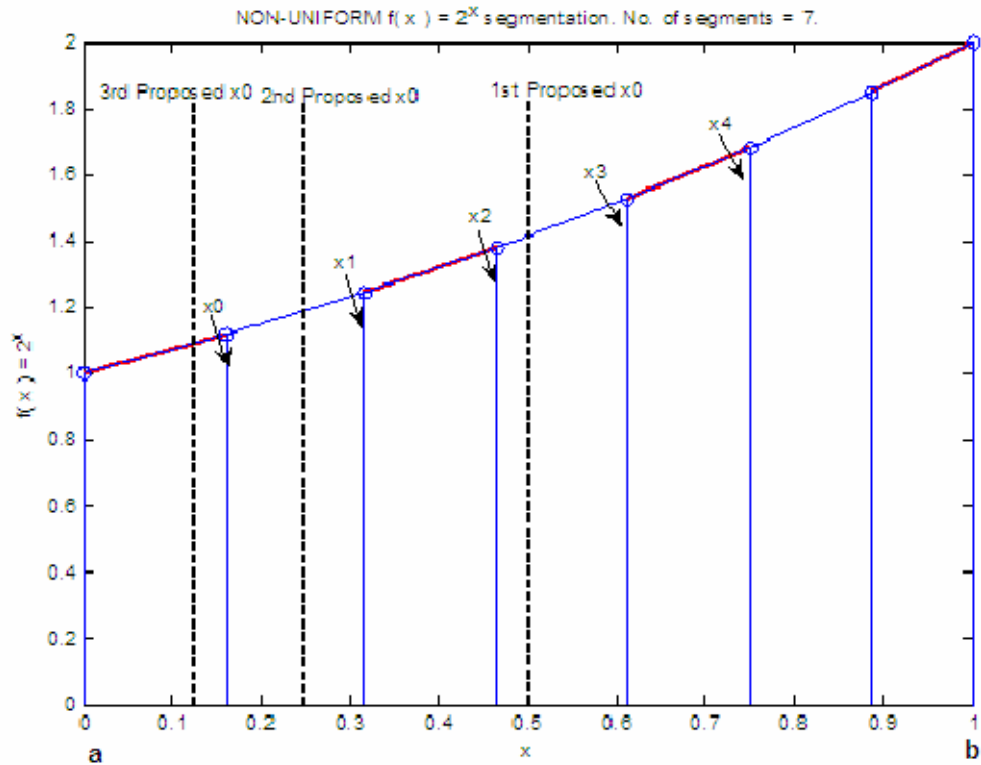


Figure 11. Shows the interval and segmentation notation.

The process is repeated until the constraint is met. In Figure 11, the constraint is met on the fourth try and results in a proposed segment $[a, 3\text{rd proposed } x_0]$. Once below the optimum end point, the program increases the proposed segment endpoint until the constraint is exceeded. This means the segment is increased by half of the last width used to decrease the proposed segments. In Figure 11, the last width was $2^{\text{nd}} \text{ proposed } x_0 - 3\text{rd proposed } x_0$. The process of increasing and decreasing the segment size by widths that are halved per iteration is repeated until the width being used to increment or decrement is 1. At this point, we are done with step 1 (Locate) and we move to step 2. Step 2 uses brute force to Pinpoint the optimum segment.

The binary search finds the actual segment end point in approximately s steps as described by inequality (0.2) where $npts$ is the number of points in the initial proposed segment.

$$s \geq 1 + \log_2(npts) \quad (0.2)$$

Compared to the number of steps required by brute force, this is a dramatic improvement. Consider $N=1,000,000$, then the binary search for the first segment should yield around 21 steps to find the optimum segment end point x_0 ; $npts$ in this case is 1,000,000. The number of steps required to reach the segment end point is reduced as the program progresses to the end of the domain interval. This is because the argument $npts$ in equation (0.2) decreases. In Table 4 the *binary search* takes 924 calls to the function *chebyRemz* as opposed to the brute force method which makes 1,000,000 calls.

The number of calls to the user programmed MATLAB function *chebyRemz* is used as a metric for two reasons: (1) the code for *chebyRemz* takes longer to execute than any other piece of code in the program and (2) the number of calls to the user programmed MATLAB function *chebyRemz* will vary depending on what numeric function is being segmented. Appendix D shows a copy of *profile results* [7] that shows

the execution time of each function. The goal is to minimize the number of calls to *chebyRemz*, thus speeding up the program.

Appendix A.2.1, part b shows the portion of the program that applies this method. The file name is *varQuadApproxBinSearch.m*.

Table 4 shows the number of calls to the function *chebyRemez* for 9 different algorithms that were investigated to speedup the segmentation. The first column is the number of points used to subdivide the domain. The next 9 columns are the different algorithms and the results. Only one function and one accuracy was used; $\sqrt{-\ln(x)}$ and $\varepsilon = 2^{-17}$ respectively.

N	Binary Search	Thirds	Ratio	1 Est	2Est	3Est	Avg 1Est	Avg 3Est	Hybrid w/ Thirds & 3Avg *1.05
1 M	924	764	1143	65400	3369	1903	5972	1960	98
100 K	764	640	699	6620	430	293	697	298	98
10 K	649	529	563	739	132	127	166	129	103
1 K	488	429	450	181	114	120	128	122	117

Table 4. Various methods show the number of calls to the function *chebyRemz*; segmentation of $\sqrt{-\ln(x)}$, $\varepsilon = 2^{-17}$ and various values of N.

c. *Divide by Thirds*

A second program was implemented that applied the same principle as *binary search*, however instead of taking off half of the width, the program took off two thirds (i.e. divide the remaining width by three). Therefore this method is also a two step process:

1. Locate: A point close to the optimum point is determined.
2. Pinpoint: Use brute force to move up to the optimum point.

Figure 12 shows the segmentation for the 5th segment. The domain interval is $[a, b]$, we start the segmentation of segment 5 at the end the 4th segment; x_4 .

Step 1: Denote the unsegmented part of the interval as $[x_4, b]$. A call to the function *chebyRemez* is used to generate a quadratic approximation. This approximation is tested to see if any points exceed the constraint ε . If the constraint is met, then we have the final segment. Exit.

Step 2: Divide the initial width by three; the new value is 1/3 of the initial width. This is labeled as L1 in Figure 12. L1 is now the new proposed segment width and *chebyRemez* is called to establish a quadratic approximation for the interval. The point labeled x_5 is the optimum segment endpoint. In Figure 12, L1 is clearly not the optimal width.

Step 3: The program divides L1 by three and the result is L2. A quadratic approximation is computed to test the approximation error against the constraint. Since L2 is below the optimum point, we initialize a new variable, *delta*, to be used to keep track of the width which is being added or subtracted to the proposed width of the segment. *delta* is 1/3 of L2.

Step 4: Increase L2 by 1/3 of L2. This results in L3, which is tested to determine the approximation error. In Figure 12, L3 is still short of the optimum segment.

Step 5: Increase L3 by the same *delta*, i.e. 1/3 of L2. The approximation is computed for the new proposed segment of width L4, and the approximation error tested against the constraint. This time we have exceeded the optimum endpoint, i.e. approximation error is greater than ε . In Figure 12, L4 is larger than the optimum point.

Step 6: Since we have exceeded the optimum segment, we now reduce the variable *delta* to 1/3 of *delta*. This value is the used to reduce L4 to a narrower width, i.e. L5. In Figure 12, L5 is still wider than the optimum width.

When the increment width is 2 or less, Locate is complete and the program goes to Pinpoint. The process stops when two adjacent points straddle the optimum

segment endpoint. The lower value is x_5 , the segment endpoint for the program. Since the domain has been divided into discrete points, x_5 is just shy of the optimum point. The approximation error of the new segment meets the constraint; however, the next point to the right of the optimum point has an approximation error that exceeds ε .

The results showed an improvement over binary search. Table 4 shows that the method of *Thirds* called the function *chebyRemez* 764 times as opposed to the *binary search* method that took 924 calls to achieve the same segmentation.

Other values besides one-third were tested, but they did not perform consistently better. Appendix A.2.1, part c shows the portion of the program that applies this method. The file name is *varQuadApproxTHIRD.m*

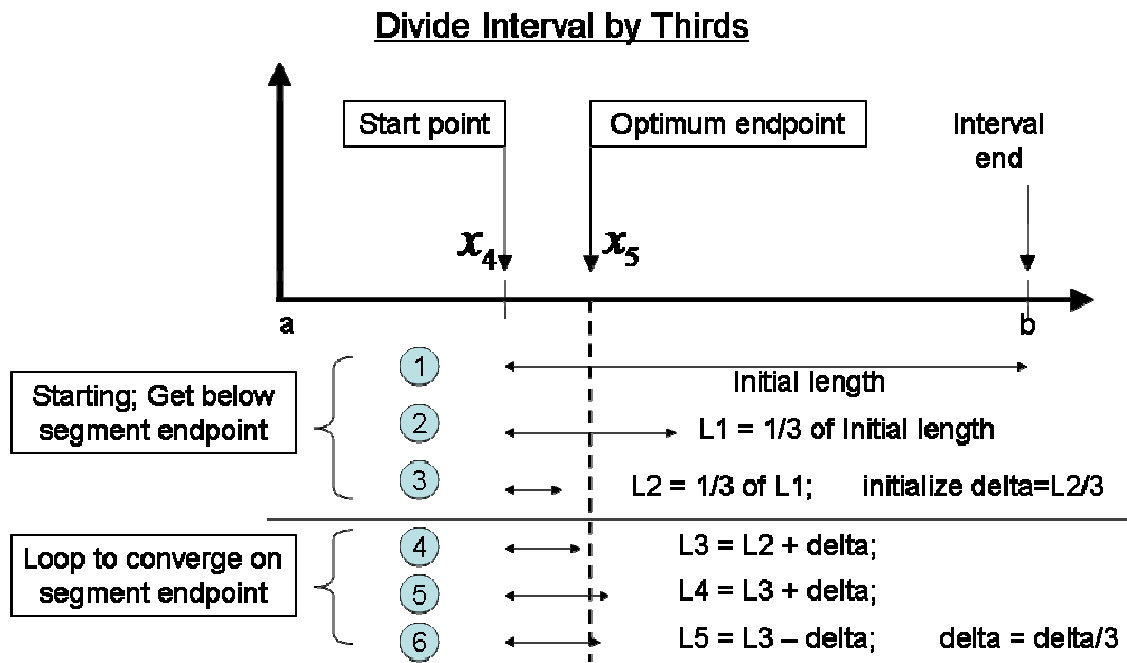


Figure 12. Visual aid for description of *divide by thirds* algorithm.

d. *Increment by Ratio Numbers*

In this method, the width of the proposed segment is increased or decreased by multiplying the current proposed width by a series of fixed values. We have the same 2-step process of Locate and Pinpoint.

In Locate, the proposed width is the entire remaining width of the domain interval $[a, b]$ i.e. the width from point a to point b . The width is tested to see if the constraint has been exceeded or not; except for the last segment, the width will always exceed the optimum segment because the entire remainder of the interval is used per iteration. As an example, consider that the first segment $[a, x_0]$ is already established (segment $[a, x_0]$ as shown in Figure 11). Next, the program needs to compute the second segment. The program will establish a proposed width $[x_0, b]$. This is the entire remainder of the interval. The ratios are applied to the width $[x_0, b]$. The result is shorter widths that are tested until the constraint is met. This method is similar to the method “*Divide by Thirds*,” except that, a set of ratios are applied to the increment/decrement width.

Table 4 shows the implementation of increment by ratio numbers took 1143 calls to *chebyRemz* function. Appendix A.2.1, part d shows the portion of the program that applies this method. The file name is *varQuadApproxRatio.m*

e. Estimated Segment Widths (1, 2, 3, more and Average)

Again, the 2-step process of Locate followed by Pinpoint is applied here. In Locate, an estimate of the segment is calculated.

Equation (0.3) is adapted from [15] to compute segment estimates for quadratic approximations. The derivation is in Appendix F. The accuracy ε , and the third derivative of the function used to estimate the width of the segments. The proposed segment widths are tested and the program falls back on the brute force method after the initial estimate. This yields a large improvement from using the brute force method alone.

$$EstSegLen = 4 \left[\frac{3\varepsilon}{\left| \frac{d^3 y}{dx^3} \right|_{\max}} \right]^{\frac{1}{3}} \quad (0.3)$$

One Estimate: In Table 4, when one estimate is used, i.e. the third derivative is computed at $x = \text{begin point of the segment}$. The estimated width is added to the begin point and the proposed segment is tested. The brute force method takes over and single steps to the optimum segment width. The result was 65,400 calls to *chebyRemez*.

Two Estimates: The first estimated width is calculated using equation (0.3) and the third derivative is computed at the begin point of the segment. The resulting estimated width is added to the begin point and the resulting endpoint is used in equation (0.3) to make a second estimated width using the third derivative at the endpoint. The average of these two widths is the estimated width that is applied to the begin point to obtain a proposed endpoint. Again, the program uses the brute force method to complete the segmentation. This method improved the performance and took 3369 calls to *chebyRemez*.

Three Estimates: Two estimates are computed as described above. The result is divided in half the half-way point is used to compute the third estimate. The third estimate is averaged with the other two estimated widths to obtain the proposed segment width. As in the other two cases, the brute force method is then applied to complete the segmentation. Even further improvement was achieved; 1903 calls to *chebyRemez*.

Estimates with more than three widths were tested, but the performance began to degrade. So, an average was applied to the segments.

Average of one estimate: In the average method, one estimate was computed from the begin point. The estimate was used to define a proposed segment. The *entire* set of points on this proposed width are evaluated using equation(0.3). Then, the mean of the resulting vector of estimated widths was computed and used as the proposed segment width. The result appeared to be similar (not exact) to taking two estimates (when multiple functions are tested, on average the results of two estimates and the average method are similar). Table 4 shows that this method called *chebyRemez* 5972 times.

Average of three estimates: This method is a combination of taking three estimates as described above. All the points on the proposed width are evaluated with equation (0.3). This creates a vector of proposed estimates. Next evaluate the mean of the vector of proposed estimates to get one estimate. The results of this method are similar to taking three estimates. However, since we evaluate all the points on the interval, it takes slightly longer.

In [15], a comparison was made to show the benefit of three estimates over two estimates and one estimate in the case of linear approximation. While it is not discussed in [15], one estimate was computed in the linear approximation and the resulting proposed width was used to compute the mean of all the estimates obtained from evaluating all the points on the proposed width. The mean of the estimates was similar to taking the mean of just two estimates (begin point and proposed endpoint). In the quadratic case, the same method yielded results that were comparable to taking the mean of two estimates, just like the results in the linear case. However, when the mean of three estimates was used to define a proposed segment and the average of all the estimates on the newly proposed width was computed, the result was very close to taking the mean of just three estimates.

Closer analysis revealed that, in many cases, the average of all the points worked well and sometimes even better than just the mean of three individual estimates. The results appear in Table 5. The first column is the suite of numeric functions represented by a number; the focus should be on the comparison, not any particular numeric function. The second column is just the three estimates as described above, the third column is the average of the estimates calculated using all points on the proposed segment. The fourth column is the difference between the second and third column. The last column is a method described in part *f*; Hybrid of Thirds and three Estimates. Table 5 shows that taking the average of all estimates on the segment has a slight advantage over taking the average of just three single estimates. Therefore, looking back, Table 4 used only one numeric function, and that made it appear that the method of $3Avg$ was slightly worse, whereas in Table 5, we can see that when applied to the entire suite of functions, the average over the entire segment (which was selected after three estimates),

was slightly better. The values at the bottom are the sum of all the calls to the approximating algorithm, *chebyRemez*, which was the metric used to determine the comparative speed of the program.

Function by Numbers	3Est	3Avg	Comparison (3Est – 3Avg)		*1.05 Hyb 3Avg
1	23	29	-6		20
2	93	103	-10		29
3	148	146	2		14
4	133	145	-12		23
5	83	84	-1		26
6	90	95	-5		23
7	266	87	179		59
8	6326	6210	116		61
9	128	92	36		35
10	293	298	-5		98
11	6233	6203	30		65
12	925	581	344		172
13	230	81	149		39
14	7378	7203	175		95
15	650	963	-313		222
SUM	22999	22320	679		981

Table 5. Comparison of “3 estimates”, mean of all estimates computed on proposed segment that was calculated after taking 3 estimates; “3 average” and a hybrid that exaggerates the approximation error by 5%. All cases, $N=100,000$ and $\varepsilon = 2^{-17}$.

The next question is; should we use just three estimates or should we use the average of all the estimates computed from all the points on a proposed segment? The difference is small. The impact of the additional code that takes the average of an

entire segment did not exceed the time taken by *chebyRemez* and did not significantly impact the computing time of the program.

The additional code does not take add significantly to the program and since it has advantages, we kept the program that averages the estimates over the entire segment. The analysis to support that decision follows: Consider the small section of a *Profile report* from MATLAB that is similar to the one in Appendix D.

Table 6 shows the total time for *varQuadApprox* implemented with only three estimates. The time for the function, including all child functions is 44.438s. These values come from running the program with the function $-(x \log_2 x + (1-x) \log_2 (1-x))$, $N=1,000,000$ and $\varepsilon = 2^{-33}$.

Profile Summary <i>Generated 21-Aug-2007 22:25:40</i>				
Function name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
multipleQuadApprox	1	44.906 s	0.156 s	
varQuadApproxHyb3EstThird	1460	44.438 s	3.516 s	
chebyRemez	13187	39.156 s	16.406 s	
inline.subsref	87050	20.031 s	3.031 s	
inlineeval	87202	17.031 s	17.031 s	
polyval	69483	3.828 s	3.359 s	
twosComp	5840	3.000 s	0.188 s	

Table 6. Profile Report for $-(x \log_2 x + (1-x) \log_2 (1-x))$, $N=1,000,000$ and $\varepsilon = 2^{-33}$. Shows 44.438s for the *varQuadApprox* function that averages only three estimates.

The same function and parameters were run with the additional code that takes the average of all estimates over the entire segment. The results appear in Table 7. The total time for *varQuadApprox*, and all its child functions is 20.078s. The additional

code to compute the averages took 0.061s which translates to less than 1% of the time spent in *varQuadApprox*. Therefore, the additional code is negligible. This particular function clearly shows the advantage of taking the average; greater than 50% improvement (44s to 20s).

It should be noted, that, in a few cases, the improvement was not as dramatic and in $\sqrt{-\ln(x)}$, the average code performed worse by 20% (20 seconds to 25 seconds). However, on average, it was better to take the average over the entire segment.

A slightly different problem; what happens when the third derivative is zero? This presents a problem in the computation of estimates (the third derivative is in the denominator of equation(0.3)). Therefore, one way to tackle the problem is to find the smallest non-zero, third derivative magnitude over the entire domain interval $[a, b]$ and use that to calculate the largest expected segment. This large segment is substituted whenever the third derivative is zero. In many cases, the resulting estimate is a poor estimate of the segment size, and tends to slow down the program when encountered. Therefore, a hybrid of the best segmentation processes was used and is described below.

varQuadApproxHyb3AvgThird (1462 calls, 20.078 sec)

Parents (calling functions)

Filename	File Type	Calls
multipleQuadApprox	M-function	1462

Lines where the most time was spent

Line Number	Code	Calls	Total Time	% Time	Time Plot
98	[p,oscil,errP] = chebyRemz(fct...	1462	4.531 s	22.6%	<div></div>
194	[p,oscil,errP] = chebyRemz(fct...	994	3.375 s	16.8%	<div></div>
209	[p,oscil,errP] = chebyRemz(fct...	1001	3.141 s	15.6%	<div></div>
182	[p,oscil,errP] = chebyRemz(fct...	945	2.859 s	14.2%	<div></div>
133	[p,oscil,errP] = chebyRemz(fct...	1010	2.719 s	13.5%	<div></div>
Other lines & overhead			3.453 s	17.2%	<div></div>
Totals			20.078 s	100%	

<

Table 7. Profile Report for $-(x \log_2 x + (1-x) \log_2(1-x))$, $N=1,000,000$ and $\varepsilon = 2^{-33}$. Shows 20.078s for the *varQuadApprox* function and 0.061s for the average of all the estimates on the entire segment.

f. Hybrid of Thirds and 3 Estimates

In this algorithm, we take advantage of the strengths of two programs. As with the other algorithms, we have a Locate and Pinpoint step. However, Locate is a combination of *Divide by Thirds* and *3 Estimates*.

We know that ε is the constraint and that when the approximation is good, then a ratio of the maximum approximation error to ε should be very close to 1.0. This ratio can be used as a metric to determine the quality of our estimate. If the ratio is much larger than 1.0, because the segment is too large, then our estimate is too wide. If it is much less than 1.0, our estimate is too small.

To take advantage of the ratio of approximation error and ε , the program first takes the average of the three estimates and using the estimated width, computes the approximation error. If the ratio of the approximation error to ε is large (greater than 1.002) or small (less than 0.9) the program takes the estimated width as a starting width. The program then takes a small fraction of that width (5%) and stores it in a variable that is used to decrease or increase the proposed width. The algorithm used is *Divide by Thirds*.

In addition to the steps taken above, the program was modified to exaggerate the error calculated from the approximation. This only happens in the final steps when trying to Pinpoint the end of the segment. This has two effects:

(1) It drastically reduces the number of steps required because many of the estimations fall short and by exaggerating the error when the segment falls short, you reduce the distance that Pinpoint has to travel to exceed ε . If you combine the effect of saving two or three steps per segment, it adds up to 100 steps if the segmentation produces 33 segments.

(2) Exaggerating the approximation error has the effect of making some of the segments slightly smaller than they would otherwise be if the approximation error were not adjusted. However, remember that the final segment is usually truncated and therefore can absorb the extra space created by making the previous segments narrower. In a way, by decreasing the size of the each segment by a small amount, it builds in a little slack per segment because the approximation error is slightly smaller than ε . The truncated segment is not optimized and can be increased to accommodate the small adjustments in all the other segments. Only in the very high precision segmentation do the segments increase noticeably. The increase is on the order of single digits when

considering hundreds or thousands of segments. This compromise is acceptable because it dramatically reduces the number of calls to *chebyRemez* as shown in the last columns of Table 4 and Table 5. Further, it does not increase the segments by any significant amount.

This hybrid method produces by far the best solution among all the algorithms discussed. Consider the function, $\sqrt{-\ln(x)}$, as shown in Table 4, only 98 calls to *chebyRemez* were needed to achieve segmentation, which is 0.0098% of the steps that brute force would take when $N=1,000,000$.

C. MATLAB RESULTS

MATLAB was used to segment the numeric functions into piecewise quadratic segments. The uniform and non-uniform segmentation, number of segments required for each of the numeric functions and a comparison of the segmentation algorithms have been discussed in part B above.

The coefficients that represent the piecewise quadratic approximation for the segments are computed and stored in a file. These files can store the coefficients and segment boundaries in hexadecimal, binary or decimal form. The NFG implemented in the floating point number representation, uses the coefficients saved as decimal values. However, when the NFG is in fixed point number system, the coefficients saved are hexadecimal values.

Table 8 shows the data in the memory file for the non-uniform segmentation of $\cos(\pi x)$. At the top of the memory files is a decimal number that states the number of segments in the memory file. This is useful when reading the file to determine how many elements need to be read into the program.

460			
0.004610004610	-4.934645942292	-0.000000373180	1.000000000116
0.007928007928	-4.933831217369	-0.000007964422	1.000000018030
0.010830510831	-4.932649394425	-0.000026748228	1.000000092899
0.013492513493	-4.931191898804	-0.000058351444	1.000000264447
0.015989015989	-4.929503741104	-0.000103932118	1.000000572352
460			
0x000000970f858467	0xffffd885d8592426b	0xffffffffffffcde9a16	0x0000800000003fff4
0x00000103c8f362f9	0xffffd887837fab57d	0xffffffffffffbd3088d1	0x0000800000026b814
0x00000162e4e8e873	0xffffd889ef1d427ca	0xffffffffffff1f9e9e52	0x00008000000c77ff1
0x000001ba1f681879	0xffffd88ceb4302ae2	0xffffffffffe16833aaf	0x000080000237e533
0x0000020bed96624f	0xffffd8906057b39b1	0xffffffffffc982779e8	0x0000800004cd1dc1

Table 8. Sample memory-files (Decimal and Hexadecimal). Non-uniform segmentation of $\cos(\pi x)$, $N=1,000,000$ and $\varepsilon = 2^{-33}$.

The first column shows the segment end points. The next three columns are the coefficients of the quadratic polynomial that determines values in the segment. The order is c_2 , c_1 and c_0 from left to right. Equation (0.4) shows the relationship of the coefficients to the polynomial.

$$f(x) = p = c_2 x^2 + c_1 x + c_0 \quad (0.4)$$

The hexadecimal values in Table 8 use a fixed point number system, where the first 17 bits are the integer including a sign bit and the last 47 bits are the fraction. The number is a two's complement number. The number system is discussed in section III.

D. SUMMARY

MATLAB is used to segment the suite of functions in Table 1. The segmentation algorithm results in the fewest segments for a given accuracy constraint. In each segment

the *minimax* quadratic approximation is achieved by computing the coefficients using the *Remez* algorithm which performs better approximation than MATLAB's available function; *Polyfit*

The *Remez* algorithm is slow; therefore various methods were investigated to find an efficient algorithm to compute the segmentation of the numeric functions. A hybrid of three algorithms is chosen as the best algorithm to compute fast segmentation of the suite of functions. Table 4 uses only one function, but summarizes the results of the comparisons.

Quadratic segmentation at high accuracy (2^{-33}) results in over 96% fewer segments, compared to linear approximation as shown in Table 2.

The segmentation is the first step to building the NFG. Next the circuit has to be designed in hardware. In section III, we look at the components that make up the NFG circuit.

III. NFG CIRCUIT

A. CIRCUIT OVERVIEW

Figure 1 is duplicated here from section I for convenience. Figure 1 shows three multipliers, the segment index encoder, coefficients table and one 3-input adder. These are the hardware components for the NFG.

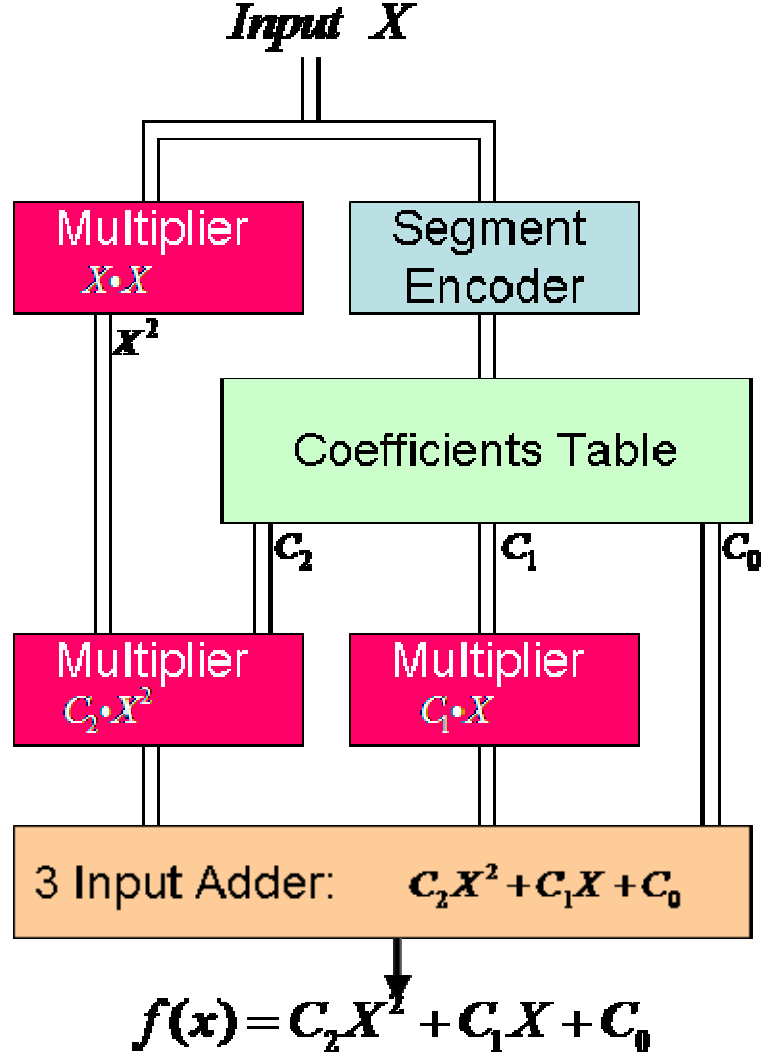


Figure 1. NFG Overview (duplicated from Section I).

The architecture has three 64 bit multipliers and one 3-input 64 bit adder. The adder and multiplier can be implemented in two's complement or floating point by using the prescribed math operators. To generate a floating point multiplier or adder, the operands need to be declared as doubles or floats. To generate a two's complement multiplier or adder, each operand needs to be declared as an integer, e.g. *int64_t* or *int*.

The segment index encoder is designed using a priority selector macro supplied by SRC and provided as a user callable macro. In uniform segmentation, multiplying by a segment density number can obtain the desired index.

1. Number System

To determine the number system to use, we need to know the range of values the NFG will have to handle. An analysis of the domain, range and coefficients provides the boundaries for the number system.

Table 9 shows the analysis of the numeric functions. The numeric functions have been ordered to show the most demanding to the least demanding. At the top, $\sqrt{-\ln(x)}$ requires 15 bits to accommodate any integer value the hardware may encounter, based on the range of values and coefficients.

The columns, *Max* and *Min* are the maximum and minimum values among all coefficient values, all possible domain and range values, i.e. any number that would appear in the computation done by the NFG. The column labeled *log2(abs(largest one))* is obtained by comparing the absolute value of *Max* and *Min* and choosing the larger. We then compute the logarithm base 2 of this value. The final column shows the maximum number of bits required to represent the largest possible integer the NFG may encounter. Note that these values have been computed for a specific domain and different domains may require more or less bits. Table 2 shows the domains for each of the numeric functions that appear in Table 9.

The NFG requires at least 15 bits to represent the largest integer that may be encountered when computing the approximation of a numeric function. Therefore, the number system chosen is 16 bit integer and 16 bit fraction (i.e. 32 bit implementation). A

64 bit implementation has 32 bit integer and 32 bit fraction. The decimal point in the two's complement number system is interpreted to be between bit 32 and bit 31 in a 64 bit number when the LSB is 0.

The 64 bit implementation benefits from using a 16 bit integer and 48 bit fraction, however the number of segments required is very large and these implementations were not investigated in detail. As an example, $\cos(\pi x)$ at $\varepsilon = 2^{-49}$ and $N=5,000,000$ would require 19,167 segments.

Function	Max	Min	log2 (abs(largest one))	Number of bits Required
$\sqrt{-\ln(x)}$	24047.26212	-196.4301496	14.55358503	15
$-(x \log_2 x + (1-x) \log_2(1-x))$	360.5900787	-185.0149295	8.494215892	9
$\tan^2(\pi x) + 1$	78.89563478	-26.88144904	6.301873574	7
$\sin(e^x)$	94.22597144	-96.6450472	6.594623895	7
$\tan(\pi x)$	19.70724959	-3.570442576	4.300654538	5
$\ln(x)$	4.934751084	-4.934751014	2.302977315	3
$\sin(\pi x)$	1.569925541	-4.934645908	2.302946566	3
$\cos(\pi x)$	1.569925541	-4.934645908	2.302946566	3
$1/x$	2.997676487	-2.995354324	1.583844694	2
$\log_2(x)$	2.882537585	-2.162615784	1.527339419	2
2^x	1.093679242	0.004061004	0.129189682	1
\sqrt{x}	2	-0.124634328	1	1
$1/\sqrt{x}$	2	-1.247861112	1	1
$\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$	1.414213562	-0.414997832	0.5	1
$\frac{1}{1 + e^{-x}}$	1	-0.045379009	0	0

Table 9. Maximum and minimum values encountered for each function in the NFG computation. Last column is the number of bits required for the integer portion.

2. 16, 32, 64 Bit Accuracy vs. 16, 32, 64 Bit Architecture

The accuracy and architecture can be built to match each other. Consider a set of values of 16 bit accuracy. Based on the number system, we would need 16 bits for integer and 16 bits for fraction (which is the accuracy). An architecture that matches these needs has to have 32 bit words; the architecture would be 32 bits. One implementation in the NFG was designed this way. Another design was built with 32 bit accuracy (32 bits fraction and 32 bits integer) and therefore the width of the architecture is 64 bits.

Another way to build the NFG is to use 64 bit architecture for all accuracies. This means that all values will be represented in 64 bits. Consider a value that is accurate to 16 bits. In this case, 32 bits are available to represent the fraction, but the fraction will only be accurate to 16 bits. The rest of the bits are irrelevant, but the hardware operates on all 64 bits. The architecture, in this case, does not match the accuracy.

B. CIRCUIT COMPONENTS

1. Segment Index Encoder

The segment index encoder accepts input (x) values (within the domain of the NFG) as inputs and outputs a number used to obtain the quadratic coefficients. The number is an index to the segment that x belongs. This only applies to the non-uniform segmentation.

User callable macros available in the SRC are used to implement a priority selector in the NFG. The prioritized selectors work as an “if-else-if” sequence. A wide number of options are available for 8, 16, 32 and 64 bit wide values. Each of these bit widths options can be implemented with 4, 8, 16, 32, 64, 128 or 256 elements. For example, choosing 64 bits and 256 elements, is equivalent to a priority encoder of 256 64 bit words.

The prioritized selector requires a Boolean condition and an assignment for a true condition. In the NFG, the Boolean condition is the comparison of the segment endpoint to the input value (numeric function argument; x). If x is less than the segment endpoint,

then x belongs to that segment and the corresponding assignment value is the index of the segment. Since x lies in the chosen segment, the index of the segment is used to access the polynomial coefficients that approximate the numeric function in that segment.

The types of selectors for a given segmentation are carefully chosen so as not to use more FPGA area than necessary. For example, consider a numeric function that has been segmented into 48 segments. The only selector that would accommodate this number of segments is the 64 element selector or greater. The 64 element selector can handle another 16 elements. However, since we do not need them, the whole selector wastes 48 elements. A better approach is to make two smaller selectors out of one 16 element selector and one 32 element selector. This saves FPGA area and allows us to build the selector we need. An example of the described code is provided in Table 10

```
//--Select Which Switch Statement will be executed---//
if ( varx <= 0.333333333333333310)
    sel = 1;
else if ( varx <= 0.500000000000000000)
    sel = 2;

//-----Switch Statement-----//
switch (sel)
{
    case 1:
        select_pri_64bit_32val( varx <= 0.010351035103510351,    0,
                                varx <= 0.020802080208020803,    1,
                                varx <= 0.031203120312031204,    2,
                                .
                                .
                                .
                                varx <= 0.322882288228822870,    30,
                                31,    &indx);

        break;
    case 2:
        select_pri_64bit_16val( varx <= 0.343734373437343750,    32,
                                varx <= 0.354135413541354140,    33,
                                varx <= 0.364586458645864590,    34,
                                .
                                .
                                .
                                varx <= 0.479147914791479170,    45,
                                varx <= 0.489598959895989620,    46,
                                47,    &indx);

        break;
}
```

Table 10. Code that uses two selectors to implement 48 segments.

To implement a larger than 256 selector, a combination of available selectors can be used. In the *.mc* file, an *if-else-if* statement precedes the set of selectors and selects which one of the selectors will be used to encode the index.

More detail on the various selectors available in the SRC, is provided in Appendix A.10 of [17].

2. Indexing in Uniform Segmentation

In uniform segmentation, a number that is multiplied by the input value, x , is used to compute the appropriate segment; essentially, a segment number density. It represents the number of segments per unit length. Instead of a segment index encoder, x is multiplied by the segment density number and the integer result is the index that is applied to the coefficients' arrays to access the coefficients for the quadratic approximation.

The segment density number is obtained by dividing the entire interval by the number of segments and inverting the result.

For example, consider an interval, $[0, 0.5]$ with uniform segmentation. If 100 segments are realized, then the number used to multiply all inputs is $\left(\frac{0.5-1}{100}\right)^{-1} = 200$. If the input is 0.3356, then the coefficients will be extracted from the OBM array using the index $67 \left(\text{floor}(0.3356 \times 200 = 67.12) = 67 \right)$.

If the interval of the domain starts at a non-zero value, then the index obtained from the above method will be offset. Simply subtract the offset from the index obtained to get the true index into the array. This extra step increases the pipeline depth of the NFG. The effect is greater in floating point implementation compared to fixed point implementation.

a. Floating Point Implementation

The uniform segmentation of the NFG in floating point requires three files; *main.c*, *<subroutine>.mc* and *memoryFile*. An array containing floating point values of the endpoints and coefficients of the uniform segmentation are passed into the OBM, via a DMA call. The sample points for testing the NFG are placed in a separate array and passed into OBM via a second DMA call. The memory file contains three numbers at the beginning of the file:

- The number of segments (which is also the number of sets of coefficients in the memory file). Stored as an *int*.
- The segment density number that is used to determine the segment that any x input belongs to. Stored as a *double*.
- The offset value (needed for functions that have an interval with a non-zero begin point)

b. Fixed Point Implementation

The uniform segmentation, fixed point implementation, works similar to the floating point implementation. Three files are needed; *main.c*, *<subroutine>.mc* and *memoryFile*. The coefficients in the memory file and in the computation are two's complement hexadecimal numbers, as described in the section on number systems. The memory file contains three numbers at the beginning of the file:

- The number of segments (which is also the number of sets of coefficients in the memory file). Stored as an *int*.
- The segment density number that is used to determine the segment to which any x input belongs. Stored as an *int64_t*.
- The offset value (needed for functions that have an interval with a non-zero begin point)

The computation of the index, and therefore, the segment, is accomplished in two's complement. One major problem exists in this multiplication; the product is 128 bits, but the architecture only allows 64 bits to be stored. This means the upper 64 bits are truncated. In addition, since the decimal point in the operands is 32 bits from the LSB, the decimal point in the product is between bit 63 and bit 64 (when LSB is

considered to be bit 0). This means we lose all integer values and the entire product that is stored is only the fraction portion of the true 128 bit product.

To represent the full range of numbers in the numeric functions, we need to retrieve some of the upper bits. The segment density number is normally a whole number (without value in the fraction); occasionally the segment density number may have a small but negligible fraction. We can perform a 16 bit logical shift right to the segment density number without a large loss. This opens up 16 bits in the integer part of the product; which is really the index into the array of coefficients. 16 bits is enough to represent over 65,000 segments². The product is then shifted 48 bits to the right to give an index number (index numbers must be whole numbers). This method is prone to rounding errors which occasionally result in the wrong index.

Other schemes have to be implemented when both operands have a significant amount of data in the fraction. The section on the two's complement multiplier discusses other schemes in more detail.

3. Coefficients Table

The coefficients to the quadratic equation for each segment are stored in an array in the OBM banks on the MAP[®] board. The segment index encoder provides an index into the array. The coefficients are accessed and applied to the quadratic equation along with the x value that is being evaluated.

4. Multiplier

The three multipliers shown in Figure 1 are either implemented in two's complement or floating point. Floating point operations increase the pipeline depth, but are easier to code.

² The largest number of segments is 34,483, which is the uniform segmentation of $\sqrt{-\ln(x)}$, when $\epsilon = 2^{-35}$. Table 12 shows the number of segments for various functions when using uniform segmentation.

a. Floating Point Multiplier

The floating point multipliers implemented in the NFG are implicitly instantiated. The operands are declared as doubles and when the multiplier operator in the *.mc* file was applied, the MAP[®] compiler builds the floating point multiplier.

b. Two's Complement Fixed Point Multiplier

The three main categories of interest are:

- Fixed point two's complement multiplier
- Floating point multiplier
- Signed Magnitude multiplier

The signed magnitude multiplier was not built. The fixed point multipliers implemented in the NFG are either implicitly instantiated or explicitly built in HDL. The two's complement fixed point multiplier was built in Verilog, VHDL and implicitly instantiated by the SRC MAP[®] with various levels of success.

To implicitly instantiate the two's complement multiplier, the operands are declared as integer values (*int64_t*) and when the multiplier operator in the *<subroutine.mc>* file is applied, the MAP[®] compiler builds the appropriate multiplier.

This method has two major problems; (1) The SRC 64bitx64bit multiplier does not result in a 128 bit product. Instead, it results in a 64 bit product that is composed of only the lower 64 bits. (2) If the MSB at the cutoff is a binary 1, the number appears as a negative number, even though it is really a positive number.

Because of the number system chosen, i.e. 32 bits of integer and 32 bits of fraction, multiplication results in a product that represents only the fraction portion of the multiply; the integer portion, bits 65 through 128, are truncated.

One way to overcome this limitation is to choose a different number system that has fewer bits to represent the fraction, but this reduces the accuracy of the NFG and it still limits the size of the integer. The integer must be at least 16 bits to provide full coverage of the values encountered in the suite of functions in Table 1. One

implementation of the NFG was built by shifting the operands right 8 bits, before the multiply. This allowed for 16 bits to be represented in the integer portion of the product. In this case, the best accuracy that one would expect to attain is 24 bits, i.e. 2^{-24} . Due to truncating the operands, error is propagated to the output and the accuracy is not reliable. Shifting values presents another problem, because, if the MSB is a binary 1, then the right shift operation will sign extend the number. This has unwanted effects. A product may be positive, but if the bit right before the cutoff point is a binary 1, the shifted values will be sign extended and we have to zero out the leading bits. More detail on the results of this method can be found in section V where the implementation results are covered.

The best solution is to build an HDL multiplier that can compute the result in the number system chosen and therefore keep the desired accuracy and the best range for the integer without any sacrifices to accuracy. The problem with this method is that it requires a long carry chain.

Verilog or VHDL can be used to explicitly build the multipliers. Several multipliers were built in VHDL and Verilog. The HDL files do not meet the timing requirements while running the NFG, although the program compiles without any errors. Simulation using Modelsim and Xilinx ISE showed that the design for the multipliers was correct. The problem appears to be the carry chain that is required to add all the partial products.

Further investigation is needed to determine if indeed the problem is in the carry chain and if a carry save adder (CSA) followed by a carry lookahead adder (CLAH) are required. (Which were not built)

5. Adder

The NFG required a 3-input adder. As in the case with the multipliers, floating point and fixed point adders are instantiated by the MAP[®] compiler.

C. SUMMARY

The NFG circuit requires three multipliers and one 3-input adder. Floating point implementation is easier than the fixed point implementation, but requires more hardware. The multipliers can be instantiated implicitly or in the case of fixed point, the user has the option to explicitly build the multiplier in HDL.

Fixed point arithmetic presents some challenges with rounding and truncating of the operands and results.

The circuit design was built on the SRC-6E reconfigurable hardware. Section IV provides a background on the SRC-6E system to give a better understanding of the hardware and software system.

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IV. SRC BACKGROUND

A. INTRODUCTION

The late Seymour Cray established SRC Computers Incorporated in Colorado Springs, Colorado in 1996. SRC developed the IMPLICIT+EXPLICIT™ architecture that is designed to provide increased performance over conventional processors [16].

1. IMPLICIT+EXPLICIT™ Architecture

The IMPLICIT+EXPLICIT™ architecture allows the full integration of Dense Logic Device (DLD) technology such as ASIC devices or microprocessors with reconfigurable Direct Execution Logic (DEL). SRC's Carte™ Programming Environment lets the programmer choose that part of code that executes in the fixed logic (i.e. microprocessor - implicit) and that part that executes in the reconfigurable hardware (explicit) [16]. Figure 13 is an overview of the SRC IMPLICIT+EXPLICIT™ architecture.

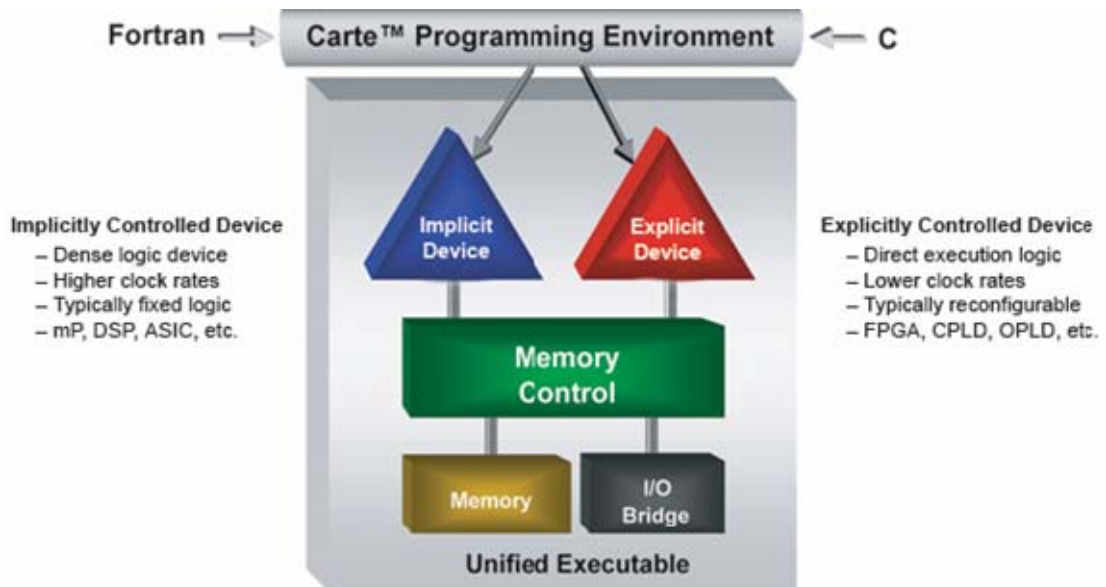


Figure 13. IMPLICIT+EXPLICIT™ architecture [16].

The user can program in the Carte™ Programming Environment in C or FORTRAN instead of designing logic. A single executable is generated that specifies which operations execute on which parts of the system. If the programmer desires to design the logic, he/she can design in a schematic capture program and generate VHDL or Verilog files that are used as macros. The user can also code the Verilog and VHDL files and use them as macros. More information on what is needed to implement macros is provided in the section on software code [16].

B. HARDWARE

Figure 14 shows 3 Xilinx XC2V6000 FPGAs on the MAP®, 2 sets of memory and some ROM.

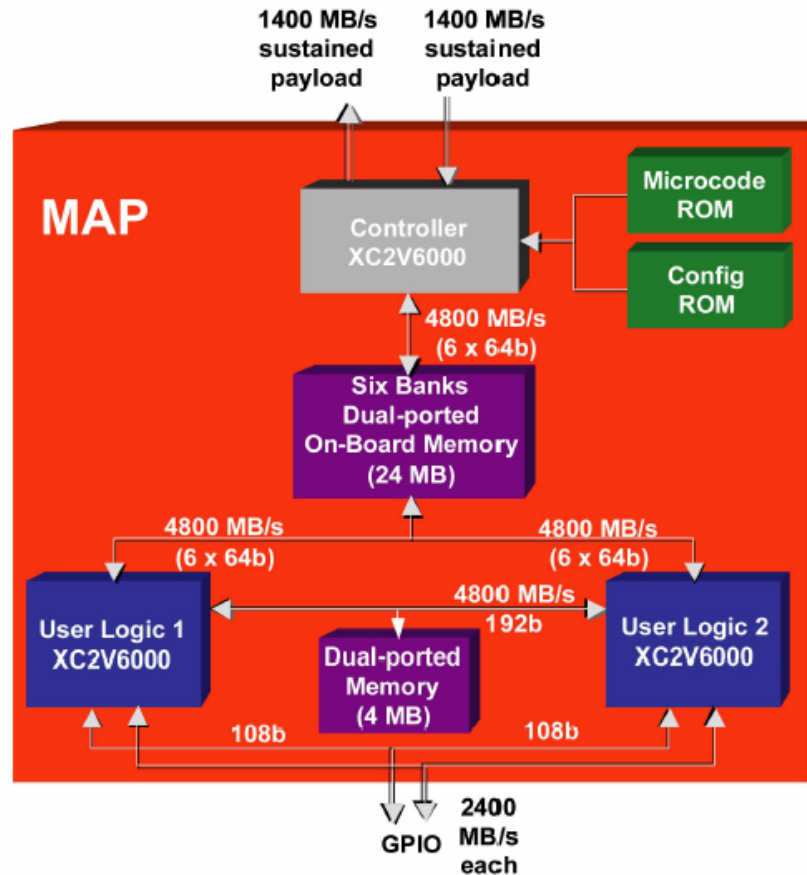


Figure 14. MAP® Hardware overview diagram [18].

There are three FPGAs. The user can program two of the FPGAs, while the third is used as a controller. The FPGAs are Xilinx Virtex II's, XC2v6000 with a -4 speed grade. There are 6 banks of dual ported On-board Memory (OBM) with a total of 24 MB (high-speed local memory). The OBM RAM is connected to the two user logic FPGAs via a 4800 MB/s (OBM RAMs is also connected to third FPGA via another 4800 MB/s bus).

The two FPGAs are connected directly to each other with access to a 4 MB dual ported memory bank for inter-chip data exchange on a 4800 MB/s bus. The two FPGAs have two General purpose I/O (GPIO) ports for direct data off the MAP[®] that is connected via a 2400 MB/s bus.

Internal to each user FPGA is an additional 144 BRAM 18KB blocks [19] for a total of 2,592 KBs of BRAM. BRAM is fast since it is on the FPGA chip.

C. SOFTWARE CODE

A user program consists of two C programs, *main.c* and *<subroutine>.mc* as well as “helper” files.

1. **main.c**

The *main* routine is a C program that runs on the SRC's Intel processor. The *main* routine contains the declarations for the subroutine functions and makes the subroutine functions visible to the Intel processor.

To effectively use the MAP[®] hardware, we need to partition the code and select the portions that will provide improved overall performance when executed on the MAP[®] processor. These include loops that can be pipelined, or manipulation of bits that are in a long bit stream of data [20]. They are placed in a C program described in the next section.

2. <subroutine>.mc

These are the files that contain the function subroutine that is called from the *main* routine to execute on the MAP[®] boards. The code in the *.mc* files should not contain any external calls outside the MAP[®] with the exception of SRC-defined or user-defined macros.

The *.mc* file does not allow any system calls or runtime functions that require intervention from the operating system. The only exception is the *printf* statement which is ignored during compile time except in debug mode; the *printf* statement is very handy in the debug mode. This means that *.mc* cannot contain any additional system header files besides the *libmap.h* header file, which is the only runtime library allowed in the MAP[®] [16].

3. Makefile

Many files are used during compilation. The *Makefile* identifies the files and commands that are used by the compiler. The *Makefile* allows the programmer to set the source code preprocessing environment variables, C compiler flags, MAP[®] compiler flags and simulation compiler flags [16]. SRC provides a template that can be tailored for the specific needs of the program.

4. Macros

Macros allow the programmer to design in HDL. It is more flexible than just the *<subroutine>.mc* file alone. Macros allow the programmer the flexibility of creating specific and unique hardware that can manipulate wide bit values and all the way down to single bits.

To implement a macro, the *Makefile* needs to know where to find the HDL files and the macro support files. The following are required for macros:

a. *info*

The *info* file provides the MAP[®] compiler with the name of the macro and the relationship between the call and the macro instantiation. The *info* file defines the name, characteristics (such as whether the macro is pipelined), whether it interacts with external systems (outside the code block), the latency of the circuit specified by the macro, the number of inputs and outputs. The signal names and macros in the Verilog code that is generated by the MAP[®] compiler requires the *info* file in order to correctly map the operators and calls in the source program [16].

The *info* file can also be used to define the behavior, in C, that the hardware is expected to perform. This feature is available for the debug mode and uses the Intel processor to emulate the hardware that the programmer intends to design on the MAP[®].

If multiple macros are used, the user only needs one *info* file. The information associated with the different macros must be put into the one *info* file.

b. *blk.v*

The black box file, *blk.v*, describes the macros interface. It is a simple file that tells the number of bits for each input and output and is described in a Verilog-style.

If multiple macros are used, the user must add the interface information into a single *blk.v* file.

c. *HDL Files*

The HDL files can be written in VHDL or Verilog. They are specified in the *Makefile*.

d. *Location for NGO Directory*

This location must be specified in the *Makefile* to identify the directory that will contain all the NGO files. The recommended practice is to put the NGO

directory in the same directory with all the macro information, and include the *info*, *blk.v* and *HDL* files.

The macros describe the logical design at a high level. The NGO files are used by NGDbuild to create an NGD file. The NGD file describes the logical design in terms of Xilinx primitives (basic elements in the FPGA).

D. SUMMARY

The SRC system provides flexibility, and a user-friendly interface for designing specialized hardware.

Various implementations of the NFG were built on the SRC system. The results are documented in section V.

V. IMPLEMENTATION RESULTS

A. UNIFORM SEGMENTATION

Uniform segmentation is easier to implement in terms of programming the <subroutine>.mc file. Appendix C shows the code *main.c* and *subr.mc* for uniform and non-uniform segmentation.

1. Floating Point Implementation

Two major advantages of the uniform segmentation floating point implementation are (1) the multiplier does all the work of moving the decimal point and (2) once the file is compiled, any function can be computed without having to recompile. The only requirement is to change the memory file.

The disadvantage is that floating point operations require much hardware. The complexity of using floating point is hidden from the user, but is evident in the amount of multipliers consumed and the pipeline depth required. Figure 15 shows the summary report after the compile process is completed; (i.e. after the user types *make hw*).

```
#####
#####              INNER LOOP SUMMARY              #####
loop on line 55:
  clocks per iteration:    1
  pipeline depth:         84
#####
#####              PLACE AND ROUTE SUMMARY              #####
Number of Slice Flip Flops:    17,647 out of  67,584   26%
Number of 4 input LUTs:       9,299 out of  67,584   13%
Number of occupied Slices:    11,390 out of  33,792   33%
Number of MULT18X18s:         64 out of    144   44%
freq = 100.2 MHz
#####
```

Figure 15. NFG Pipeline depth and place and route summary.

The SRC has user callable macros that are summarized in Appendix A of [20]. Figure 16 shows the difference between the pipeline depth of the NFG and the SRC user callable macro. The pipeline depth for the NFG is a 20% less than that of the user callable macro.

Figure 16 also shows the place and route information associated with mapping both the NFG and SRC's user callable cosine macro. Comparing Figure 15 with Figure 16, one can see the hardware requirements have increased due to adding SRC's user callable macro.

```
#####
#####              INNER LOOP SUMMARY              #####
loop on line 55:
  clocks per iteration:    1
  pipeline depth:         84

loop on line 72:
  clocks per iteration:    1
  pipeline depth:         105
#####
#####              PLACE AND ROUTE SUMMARY              #####
Number of Slice Flip Flops:    27,557 out of 67,584    40%
Number of 4 input LUTs:       17,318 out of 67,584    25%
Number of occupied Slices:    17,862 out of 33,792    52%
Number of Block RAMs:         1 out of 144            1%
Number of MULT18X18s:         92 out of 144           63%
freq = 100.0 MHz
#####
```

Figure 16. Pipeline depth (NFG and SRC Cosine Macro). Place and route summary.

Table 11 shows a comparison of the hardware used to build the NFG, the macro and both on the same FPGA. The comparison shows that the NFG approximation is close to the macro in terms of hardware needed; with the exception of the multiplier. The NFG requires a slightly more than double the multipliers that the macro requires.

	NFG Alone	Macro Alone	NFG & Macro
# of Slice Flip Flops	26%	21%	40%
# of 4 input LUTs	13%	14%	25%
# of occupied Slices	33%	27%	52%
# of Block RAMs	0%	1%	1%
# of MULT18X18s	44%	19%	63%
Freq	100.2 MHz	100.1 MHz	100.0 MHz

Table 11. Comparison of NFG uniform segmentation and macros: NFG alone, Macro alone and both (function is $\cos(\pi x)$). Implementations without offset.

The implementation described above applies to functions that have a domain interval that starts at zero. If the interval starts at a non-zero value, then the index computed needs to be adjusted by an offset value. Figure 17 shows the hardware requirements when the offset is applied.

#####	INNER LOOP SUMMARY	#####
loop on line 56:		
clocks per iteration:	1	
pipeline depth:	98	
loop on line 74:		
clocks per iteration:	1	
pipeline depth:	127	
#####	PLACE AND ROUTE SUMMARY	#####
Number of Slice Flip Flops:	29,306 out of	67,584 43%
Number of 4 input LUTs:	20,678 out of	67,584 30%
Number of occupied Slices:	20,125 out of	33,792 59%
Number of Block RAMs:	1 out of	144 1%
Number of MULT18X18s:	72 out of	144 50%
freq = 100.0 MHz		
#####		#####

Figure 17. Pipeline depth (NFG and SRC $\sqrt{-\ln(x)}$ implemented in macros). Place and route summary with subtraction hardware included for computing offset (when finding the index. of coefficients).

The adjustment is a subtraction operation. In the floating point number system, the hardware required to perform arithmetic computations is large and by adding a

subtraction computation, the NFG pipeline depth increases from 84, as shown in Figure 15 and Figure 16, to 98 as shown in Figure 17.

Figure 18 shows the comparison between the output of the macro and the NFG. The macro computes using float values, while the NFG can compute higher precision values. Therefore, a user can achieve a shorter pipeline depth and higher accuracy by using the NFG. The cost of using the NFG is that the user must have a memory file to load the coefficients of the quadratic approximation into OBM.

Figure 18 shows the comparison of the results from the NFG that uses a memory file with the coefficients computed with an accuracy of $\varepsilon = 2^{-33}$. This implementation has 459 segments and an accuracy of 32 bits.

The first labeled column in Figure 18 is, *x values*, which shows the values of x , which in this case are the endpoints. Based on the Remez algorithm, the end points, begin points and two other points in the middle of each segment have the worst case approximation error. Therefore, we expect to see the error of these points to be very close to the maximum error allowed for the segmentation i.e. $\varepsilon = 2^{-33} = 1.1641532... \times 10^{-10}$ (essentially at the 10th decimal place).

Excel and MATLAB are used to compute $\cos(\pi x)$. The results for Excel and MATLAB are exactly the same as shown in Figure 18, in the column labeled *Excel-MATLAB* (difference of the results is zero). The NFG output and the SRC cosine macro are compared to Excel and the results are shown in the last two columns. Figure 18 shows that SRC's macro is accurate to $\varepsilon = 2^{-23}$, which is the correct accuracy for floating point values. The NFG is accurate to within 2^{-33} . This accuracy can be increased without an increase in FPGA hardware, if desired. The cost is OBM memory to store a larger coefficients table.

x Values		NFG OUTPUT		SRC MACRO		Excel Cosine	MATLAB	Excel-MATLAB	ySRCMacro - Excel	NFG-Excel
x:	0.00089400089400090	ysubr:	0.999996055923	ySRCMacro:	0.999996066093	0.999996055923	0.999996055923	0.000000000000000000	0.00000001017031	-0.000000000000016
x:	0.00178850178850180	ysubr:	0.999984214899	ySRCMacro:	0.999984204769	0.999984214899	0.999984214899	0.000000000000000000	-0.00000001012988	-0.000000000000049
x:	0.00268300268300270	ysubr:	0.999964477019	ySRCMacro:	0.999964475632	0.999964477020	0.999964477020	0.000000000000000000	-0.00000000138820	-0.000000000000081
x:	0.00357750357750360	ysubr:	0.999936842441	ySRCMacro:	0.999936819077	0.999936842442	0.999936842442	0.000000000000000000	-0.00000002336516	-0.000000000000114
x:	0.00447200447200450	ysubr:	0.999901311383	ySRCMacro:	0.999901294708	0.999901311383	0.999901311383	0.000000000000000000	-0.00000001667436	-0.000000000000001
x:	0.00536600536600540	ysubr:	0.999857910602	ySRCMacro:	0.999857902527	0.999857910603	0.999857910603	0.000000000000000000	-0.00000000807656	-0.000000000000178
x:	0.00626050626050630	ysubr:	0.999806591898	ySRCMacro:	0.999806582928	0.999806591900	0.999806591900	0.000000000000000000	-0.00000000897243	-0.000000000000211
x:	0.00715500715500720	ysubr:	0.999747377743	ySRCMacro:	0.999747395515	0.999747377745	0.999747377745	0.000000000000000000	0.00000001777088	-0.000000000000195
x:	0.00804950804950800	ysubr:	0.999680268602	ySRCMacro:	0.999680280685	0.999680268604	0.999680268604	0.000000000000000000	0.00000001208112	-0.000000000000276
x:	0.00894400894400890	ysubr:	0.999605265006	ySRCMacro:	0.999605238438	0.999605265009	0.999605265009	0.000000000000000000	-0.00000002657168	-0.000000000000307
x:	0.00983850983850980	ysubr:	0.999522367549	ySRCMacro:	0.999522387981	0.999522367552	0.999522367552	0.000000000000000000	0.00000002042948	-0.000000000000339
x:	0.01073301073301070	ysubr:	0.999431576883	ySRCMacro:	0.999431550503	0.999431576887	0.999431576887	0.000000000000000000	-0.00000002638399	-0.000000000000372
x:	0.01162751162751160	ysubr:	0.999332893727	ySRCMacro:	0.999332904816	0.999332893731	0.999332893731	0.000000000000000000	0.00000001108489	-0.000000000000406
x:	0.01252201252201250	ysubr:	0.999226318859	ySRCMacro:	0.999226331711	0.999226318863	0.999226318863	0.000000000000000000	0.00000001284753	-0.000000000000436
x:	0.01341651341651340	ysubr:	0.999111853121	ySRCMacro:	0.999111831188	0.999111853126	0.999111853126	0.000000000000000000	-0.00000002193770	-0.000000000000469
x:	0.01431101431101430	ysubr:	0.998989497418	ySRCMacro:	0.998989522457	0.998989497423	0.998989497423	0.000000000000000000	0.00000002503456	-0.000000000000501
x:	0.01520501520501520	ysubr:	0.998859327721	ySRCMacro:	0.998859345913	0.998859327726	0.998859327726	0.000000000000000000	0.00000001818690	-0.000000000000535
x:	0.01609951609951610	ysubr:	0.998721199455	ySRCMacro:	0.998721182346	0.998721199461	0.998721199461	0.000000000000000000	-0.00000001711431	-0.000000000000568
x:	0.01699401699401700	ysubr:	0.998575184308	ySRCMacro:	0.998575210571	0.998575184314	0.998575184314	0.000000000000000000	0.00000002625699	-0.000000000000601
x:	0.01788851788851790	ysubr:	0.998421283434	ySRCMacro:	0.998421311378	0.998421283440	0.998421283440	0.000000000000000000	0.00000002793842	-0.000000000000633
x:	0.01878301878301880	ysubr:	0.998259498047	ySRCMacro:	0.998259484768	0.998259498053	0.998259498053	0.000000000000000000	-0.00000001328536	-0.000000000000665
x:	0.01967751967751970	ysubr:	0.998089829425	ySRCMacro:	0.998089849949	0.998089829432	0.998089829432	0.000000000000000000	0.00000002051732	-0.000000000000698
x:	0.02057202057202060	ysubr:	0.997912278907	ySRCMacro:	0.997912287712	0.997912278915	0.997912278915	0.000000000000000000	0.00000000879730	-0.000000000000730
x:	0.02146652146652150	ysubr:	0.997726847897	ySRCMacro:	0.997726857662	0.997726847905	0.997726847905	0.000000000000000000	0.00000000975711	-0.000000000000763
x:	0.02236102236102240	ysubr:	0.997533537859	ySRCMacro:	0.997533559799	0.997533537867	0.997533537867	0.000000000000000000	0.00000002193241	-0.000000000000795
x:	0.02325552325552330	ysubr:	0.997332350318	ySRCMacro:	0.997332334518	0.997332350326	0.997332350326	0.000000000000000000	-0.00000001580801	-0.000000000000828
x:	0.02415002415002410	ysubr:	0.997123286864	ySRCMacro:	0.997123301029	0.997123286873	0.997123286873	0.000000000000000000	0.00000001415636	-0.000000000000860
x:	0.02504402504402500	ysubr:	0.996906472609	ySRCMacro:	0.996906459332	0.996906472618	0.996906472618	0.000000000000000000	-0.00000001328664	-0.000000000000891
x:	0.02593852593852590	ysubr:	0.996681666744	ySRCMacro:	0.996681690216	0.996681666753	0.996681666753	0.000000000000000000	0.00000002346290	-0.000000000000925
x:	0.02683302683302680	ysubr:	0.996448990104	ySRCMacro:	0.996448993683	0.996448990113	0.996448990113	0.000000000000000000	0.00000000356950	-0.000000000000957
									Float Accuracy	0.00000011920929
									32 Bit Accuracy	0.00000000011642

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Figure 18. Results from Uniform Segmentation NFG compared with SRC Cosine Macro, MATLAB and Excel.

The results in Figure 18 show that the accuracy in the NFG can be increased to 33 bits. To take advantage of the uniform segmentation, we need to know the number of segments required in uniform segmentation. The quadratic coefficients for the numeric functions are stored in OBM memory. Table 12 shows the number of segments required for each of the accuracies. All the segments shown can be implemented in the NFG, even when the number of segments is as large as 34483; as in the numeric function: $\sqrt{-\ln(x)}$

Numeric Function	Number of Segments		
	$\varepsilon = 2^{-17}$	$\varepsilon = 2^{-24}$	$\varepsilon = 2^{-33}$
2^x	8	39	311
$1/x$	17	81	646
\sqrt{x}	7	33	257
$1/\sqrt{x}$	11	55	439
$\log_2(x)$	13	64	506
$\ln(x)$	12	56	448
$\sin(\pi x)$	14	70	559
$\cos(\pi x)$	14	70	559
$\tan(\pi x)$	18	88	704
$\sqrt{-\ln(x)}$	794	4017	34483
$\tan^2(\pi x) + 1$	30	151	1204
$-(x \log_2 x + (1-x) \log_2 (1-x))$	399	2013	16667
$\frac{1}{1+e^{-x}}$	5	23	178
$\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$	11	52	412
$\sin(e^x)$	125	627	5103

Table 12. Number of segments required for Uniform Segmentation computed with $N=1,000,000$ for various values of ε .

2. Fixed Point Implementation

The fixed point implementation has a shorter pipeline depth. Numeric function 2^x has a pipeline depth of 31 in fixed point and 84 in floating point uniform

segmentation. The multiplier inferred by the SRC accepts 64 bit operands and outputs a 64 bit product that contains only the lower 64 bits of the computed 128 bit product. This present a challenge when computing in fixed point number system as discussed in section III.B.4.a.

Table 13 shows the fixed point implementation without any special adjustments to the bits. The function is 2^x . The green portion of the table did not require any adjustment. In the yellow section, adjustments are required to eliminate the unintended sign extension of shifted values. The last two columns show the accuracy of the NFG. The very last column shows the accuracy when rounding is performed (rounding performed only in the final result, not at any intermediate points).

<u>Index</u>	<u>x Values</u>	<u>Excel 2^x</u>	<u>NFG Approx</u>	<u>Accurate to x Bits</u>	<u>If rounding were performed</u>
0	6905840	104972342	1049722c3	23 bits	24 bits
1	d20c146	1094364e6	109436464	24 bits	24 bits
2	13b12a4d	10e051a07	10e051983	22 bits	24 bits
3	1a419353	112dca51f	112dca498	23 bits	24 bits
4	20d1fc5a	117ca6a6a	117ca69e0	22 bits	24 bits
5	27626560	11ccecff2	11ccecf66	24 bits	24 bits
6	2df2ce67	121ea3d94	121ea3d06	24 bits	24 bits
7	3483376e	1271d1d0a	1271d1c7b	23 bits	23 bits
8	3b13a074	12c67d9f5	12c67d962	24 bits	
.	
.	
.	
24	a41a41a4	18f374a1d	18f374959	22 bits	23 bits
25	aaaaaaab	1965fea54	1965feb1d	23 bits	23 bits
26	b13b13b1	19da96753	19da96689	22 bits	24 bits
27	b7cb7cb8	1a51457f7	1a51458c6	20 bits	21 bits
28	be5be5be	1aca155ce	1aca154fc	23 bits	24 bits
.	
.	
.	
36	f2df2df3	1ee1ebf39	1ee1ec02c	21 bits	21 bits
37	f96f96f9	1f6fb0940	1f6fb084a	23 bits	23 bits
38	100000000	200000000	0	N/A	N/A

Table 13. Fixed point implementation of 2^x , no bit shifts, $N=1,000,000$ and $\varepsilon = 2^{-24}$.

Table 13 shows that the accuracy³ degrades in segments of higher index. This is expected because uniform segmentation results in segments that have varied accuracy. Figure 19 shows the error expected for uniform segmentation of 2^x , which is consistent with the results in Table 13. When implemented in hardware, this design does not meet the accuracy because the values are truncated at various intermediate points in the computation. The error propagates and magnifies the error in the result.

A bigger problem exists in indexing. In Table 13, the coefficients used to compute the NFG output for index 24, were actually coefficients intended for segment 25. The segment indexing failed to give the correct index. These problems contributed to the lower output accuracy as is seen in the second from last column in Table 13.

The advantage of using 2^x is that all values are less than 1.0 except for the last value; x is 1.0. No integers to deal with in this example.

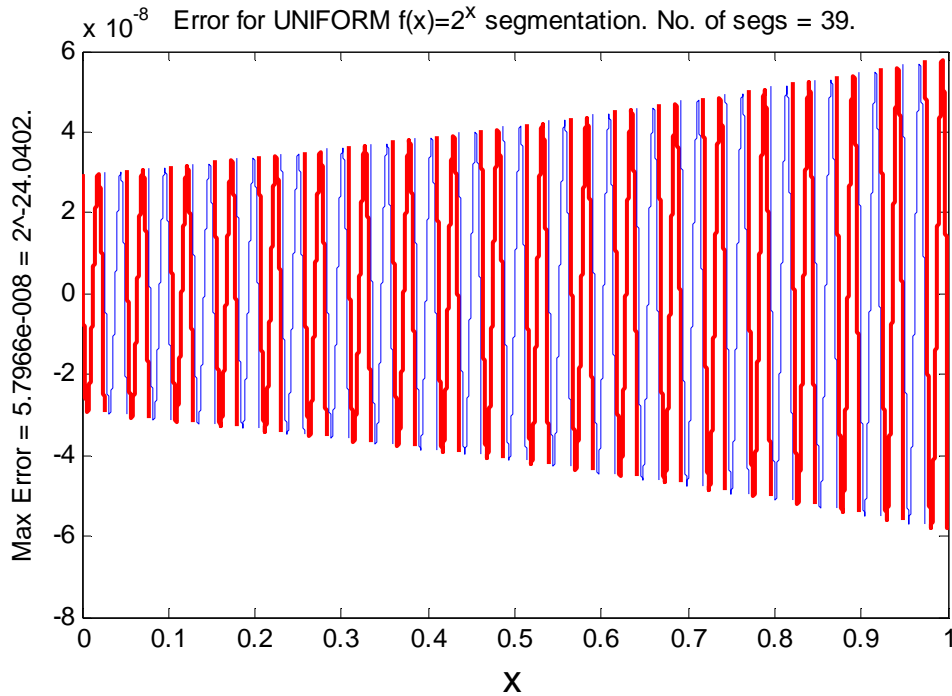


Figure 19. Uniform Segmentation of 2^x , $N=1,000,000$ and $\varepsilon = 2^{-24}$.

³ The endpoints of the segments are used as the x input values to test the numeric fractions. The endpoints have the worst case approximation error. Table 13 shows the worst case scenario.

This implementation works for only a few functions. To make it work for the rest of the functions, a better method is required to handle integers and rounding.

Table 14 shows the implementation adjusted to accommodate the integers. As described in III.B.4.b, an arithmetic shift right (8 bits) is performed on the multiplication operands before multiplication. The product now has 16 bits to represent integer portion of the product. This is enough for all the values that will be encountered in the suite of functions investigated.

The worst case function is $\sqrt{-\ln(x)}$ of large coefficients. Whenever the coefficients are very large, the impact of small numbers is larger and therefore a greater room for errors exists. When the operands are shifted, the values are truncated which causes propagation of error to the product. Last column shows the accuracy.

INDEX	x	x^2	a	ax^2	b	bx	c	fx	Accuracy
1959	1f7bb7	3df32	8b2b821	21ad89af	fffffffffb0d5a05	ffffffff6439c766	1ecb291c2	17299e2d7	25 bits
1959	1f7bb77c	3df323a	8b2b82181	21ad8ba8	fffffffffb0d5a05a1	ffffffff6439c516	1ecb291c2	17299e284	
1960	1f7fc3	3e030	8b09553	21ade3bd	fffffffffb0de083	ffffffff64364dd0	1ecaa4c9b	1728e7e28	16 bits
1960	1f7fc3b5	3e0312a	8b09553aa	21adedda	fffffffffb0de083fd	ffffffff64364a70	1ecaa4c9b	1728e84e6	
1961	1f83cf	3e12f	8ae7350	21ae4550	fffffffffb0e66e1	ffffffff6432d489	1eca20868	172832241	20 bits
1961	1f83cfce	3e1303a	8ae7350d8	21ae4ffb	fffffffffb0e66e1ad	ffffffff6432d005	1eca20868	172832868	
1962	1f87dc	3e22f	8ac5215	21aeae58	fffffffffb0eed1f	ffffffff642f56a0	1ec99c51b	17277ca13	21 bits
1962	1f87dc27	3e22f6b	8ac5215bd	21aeb200	fffffffffb0eed1f75	ffffffff642f55ec	1ec99c51b	17277cd06	
1963	1f8be8	3e32e	8aa31a7	21af0d91	fffffffffb0f733c	ffffffff642bddd6	1ec9182c8	1726c6e2f	19 bits
1963	1f8be861	3e32ebe	8aa31a702	21af13fc	fffffffffb0f733c23	ffffffff642bdbfd	1ec9182c8	1726c72c1	
1964	1f8ff4	3e42e	8a811fc	21af742b	fffffffffb0ff939	ffffffff64286557	1ec894153	172611ad5	22 bits
1964	1f8ff49a	3e42e30	8a811fcf0	21af75d3	fffffffffb0ff93990	ffffffff64286272	1ec894153	172611997	
1965	1f9400	3e52d	8a5f31f	21afd103	fffffffffb107f15	ffffffff6424ed03	1ec8100da	17255bee0	17 bits
1965	1f9400d3	3e52dc4	8a5f31f3f	21afd7a4	fffffffffb107f15ca	ffffffff6424e90a	1ec8100da	17255c189	
1966	1f980d	3e62d	8a3d508	21b03549	fffffffffb1104d2	ffffffff64217027	1ec78c14c	1724a66bc	23 bits
1966	1f980d0c	3e62d78	8a3d508d1	21b0395e	fffffffffb1104d205	ffffffff64216fec	1ec78c14c	1724a6a96	
1967	1f9c19	3e72d	8a1b7b9	21b09860	fffffffffb118a6e	ffffffff641df863	1ec7082a9	1723f136c	21 bits
1967	1f9c1945	3e72d4e	8a1b7b98d	21b09b00	fffffffffb118a6e3d	ffffffff641df714	1ec7082a9	1723f14be	
1968	1fa025	3e82d	89f9b37	21b0fa5d	fffffffffb120fe8	ffffffff641a80a5	1ec684509	17233c00b	28 bits
1968	1fa0257f	3e82d44	89f9b3736	21b0fca5	fffffffffb120fe8f7	ffffffff641a7e53	1ec684509	17233c001	
1969	1fa431	3e92d	89d7f75	21b15b0f	fffffffffb129545	ffffffff64170989	1ec60083c	172286cd4	24 bits
1969	1fa431b8	3e92d5a	89d7f754d	21b15e1b	fffffffffb1295453d	ffffffff64170607	1ec60083c	172286c5e	
1970	1fa83d	3ea2d	89b647f	21b1baa9	fffffffffb131a80	ffffffff64139271	1ec57cc71	1721d198b	25 bits
1970	1fa83df1	3ea2d92	89b647f6b	21b1bf92	fffffffffb131a8026	ffffffff64138dd2	1ec57cc71	1721d19d6	

Table 14. Fixed point, uniform segmentation of $\sqrt{-\ln(x)}$, multiplier operands shifted by 8 bits, N=1,000,000 and $\varepsilon = 2^{-24}$.

In Table 14, the first column is the index into the array. The rows show two computations; the NFG is in the colored row and the row below shows the correct values which have been computed in MATLAB and converted to the number representation. Coefficients a , b the input x and x^2 are shifted 8 bits in the NFG (colored rows). The intermediate products show the error in the intermediate steps. The two products; ax^2 and bx have been realigned before the final addition step. Table 14 shows the effect of the error as it propagates from the intermediate steps to the final answer. The last column shows the number of bits that match between the NFG output (in the colored row) and the desired output. This is basically telling how accurate the NFG has performed. As can be seen, there are instances where the error is large.

Table 15 shows the pipeline depth is 32. It also shows the summary of place and route and hardware resource requirements to implement uniform segmentation using fixed point numbers. This data is the same for all the numeric functions. The memory file determines which numeric function will be implemented.

#####			
#####		INNER LOOP SUMMARY	#####
loop on line 54:			
clocks per iteration:		1	
pipeline depth:		32	
#####			
#####		PLACE AND ROUTE SUMMARY	#####
Number of Slice Flip Flops:		8,751 out of	67,584 12%
Number of 4 input LUTs:		3,282 out of	67,584 4%
Number of occupied Slices:		5,226 out of	33,792 15%
Number of MULT18X18s:		40 out of	144 27%
freq = 100.0 MHz			
#####			

Table 15. Pipeline depth and hardware resources for uniform implementation with no adjustments.

Table 16 is a comparison of uniform segmentation between the floating point and fixed point NFG implementations. They both require the same size memory files, but the floating point hardware can handle a larger range of values than the fixed point implementation.

	Floating Point	Fixed Point	Fixed Point / Floating Point
Pipeline Depth	84	32	38 %
# of Slice Flip Flops	26%	12%	46 %
# of 4 input LUTs	13%	4%	31 %
# of occupied Slices	33%	15%	45 %
# of Block RAMs	0%	0%	0 %
# of MULT18X18s	44%	27%	61 %
Freq	100.2 MHz	100.1 MHz	0 %

Table 16. Comparison of uniform segmentation NFG between fixed point and floating point.

B. NON-UNIFORM SEGMENTATION

Non-uniform segmentation requires a segment index encoder. The SRC programming environment has a priority selector macro that is used as the segment index encoder for the NFG.

1. Floating Point Implementation

The priority selector macro in the SRC, is used as the segment index encoder. The priority selector has a limit (approximately 150 elements) when used in the NFG with three 64 bit multipliers. The non-uniform segmentation NFG, in floating point, has a pipeline depth of 74.

The math macros available in the SRC have pipeline depths that vary. For example, $\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$ implemented using the math macros has a pipeline depth of 274 as shown in Table 17. Table 17 summarizes the hardware pipeline depth for the suite of numeric functions. The table shows side by side comparisons of the pipeline depth for the NFG and the SRC math macros. In 10 of the 15 functions, the pipeline depth is smaller. For one function the pipeline depths are the same and for 4 of the functions the NFG pipeline depth is larger. Regardless of the size of the function, the NFG has the same pipeline depth; the only exception is $\sin(e^x)$. It is only one clock longer.

Three functions in Table 17 are limited by the number of segments required. In the floating point implementation with 3 multipliers and the other hardware requirements, the FPGA runs out of resources to build large priority selectors. The priority selectors were limited to approximately 150 segments. Implementations requiring larger selectors did not compile on the MAP. The data was obtained by compiling in debug mode. Some of the implementations were built in hardware, for example: $\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$.

Numeric Function	Macro Pipeline Depth	NFG Pipeline Depth	Number of Segments $\varepsilon = 2^{-24}$
2^x	132	74	35
$1/x$	70	74	50
\sqrt{x}	43	74	24
$1/\sqrt{x}$	74	74	36
$\log_2(x)$	73	74	44
$\ln(x)$	61	74	39
$\sin(\pi x)$	105	74	58
$\cos(\pi x)$	105	74	58
$\tan(\pi x)$	135	74	58
$\sqrt{-\ln(x)}$	127	74	163 ⁴
$\tan^2(\pi x) + 1$	254	74	79
$-(x \log_2 x + (1-x) \log_2 (1-x))$	114	74	183 ⁴
$\frac{1}{1+e^{-x}}$	185	74	20
$\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$	274	74	45
$\sin(e^x)$	212	75	265 ⁴

Table 17. Pipeline depth for various implementations of the available macros or the NFG in floating point number system.

⁴ Note that these numbers (number of segments) are larger than 150, and cannot be realized in priority selector in the floating point implementation.

When both the NFG and the macro are built on the FPGA, a large amount of resources are consumed and the frequency may be affected due to place and route difficulties and increased delay in the wiring. Figure 20 shows the summary of the place and route when numeric function $\frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}$ is implemented with the macros and the NFG both on the same FPGA. The frequency is 77.2MHz.

```
#####
#####              INNER LOOP SUMMARY              #####
loop on line 53:
    clocks per iteration:    1
    pipeline depth:         74

loop on line 139:
    clocks per iteration:    1
    pipeline depth:         274
#####
#####              PLACE AND ROUTE SUMMARY              #####
Number of Slice Flip Flops:    51,967 out of 67,584    76%
Number of 4 input LUTs:       39,520 out of 67,584    58%
Number of occupied Slices:    33,790 out of 33,792    99%
Number of Block RAMs:         3 out of 144            2%
Number of MULT18X18s:         90 out of 144           62%
freq = 77.2 MHz
#####
```

Figure 20. NFG and macro both built on the FPGA for numeric function; $\frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}$.

The performance improves if only one is built at a time. Figure 21 shows the same function built on the FPGA using the NFG only. The frequency is 100.0MHz.

```
#####
#####              INNER LOOP SUMMARY              #####
loop on line 53:
  clocks per iteration:    1
  pipeline depth:         74
#####
#####              PLACE AND ROUTE SUMMARY              #####
Number of Slice Flip Flops:    26,377 out of 67,584    39%
Number of 4 input LUTs:       16,386 out of 67,584    24%
Number of occupied Slices:    17,473 out of 33,792    51%
Number of MULT18X18s:         48 out of 144           33%
freq = 100.0 MHz
#####
```

Figure 21. NFG built on the FPGA for numeric function; $\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$.

Table 18 shows the results from computing $\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$, with $N=1,000,000$ and $\varepsilon = 2^{-24}$. The values are displayed to twelve decimal places. This function requires 45 segments. The values of x that are tested in Table 18 are the endpoints of the segment and therefore have the worst case⁵ approximation error. At the very bottom of Table 18 is $\varepsilon = 2^{-24}$ in decimal. The last column shows the approximation error is consistently smaller than ε ; per the design.

⁵ If the x input to the NFG were somewhere in the middle of the segment, the approximation error would be smaller. There are four points in a segment with worst case approximation error. Figure 10 is a good example to see the distribution of the approximation error on a non-uniform segment.

194 396	clocks clocks	NFG	SRC OUTPUT	Excel	SRC-Excel	NFG-Excel
x:	0.065896761049	0.398076980336	0.398077040911	0.398077039931	0.000000000979	-0.000000059595
x:	0.113411555833	0.396384819146	0.396384894848	0.396384878748	0.000000016100	-0.000000059601
x:	0.155068672183	0.394174398848	0.394174486399	0.394174458446	0.000000027952	-0.000000059598
x:	0.193392483833	0.391551192645	0.391551256180	0.391551252249	0.000000003931	-0.000000059604
x:	0.229466279456	0.388576167409	0.388576239347	0.388576227007	0.000000012340	-0.000000059598
x:	0.263888271986	0.385290687187	0.385290741920	0.385290746785	-0.000000004864	-0.000000059597
x:	0.297033228393	0.381725674206	0.381725728512	0.381725733800	-0.000000005288	-0.000000059593
x:	0.329159950016	0.377905230684	0.377905279398	0.377905290287	-0.000000010889	-0.000000059603
x:	0.360453699018	0.373849440845	0.373849511147	0.373849500448	0.000000010698	-0.000000059604
x:	0.391055896896	0.369575196048	0.369575262070	0.369575255651	0.000000006419	-0.000000059603
x:	0.421076852419	0.365097238417	0.365097314119	0.365097298012	0.000000016107	-0.000000059595
x:	0.450608489560	0.360428130051	0.360428184271	0.360428189648	-0.000000005377	-0.000000059598
x:	0.479725761713	0.355579258917	0.355579316616	0.355579318519	-0.000000001902	-0.000000059601
x:	1.010456600772	0.239440565640	0.239440649748	0.239440625229	0.000000024519	-0.000000059589
x:	1.039409823988	0.232439528403	0.232439562678	0.232439587993	-0.000000025315	-0.000000059590
x:	1.068692559293	0.225374753587	0.225374817848	0.225374813189	0.000000004659	-0.000000059602
x:	1.098347233137	0.218248244336	0.218248322606	0.218248303940	0.000000018667	-0.000000059604
x:	1.128421928829	0.211061263284	0.211061343551	0.211061322887	0.000000020664	-0.000000059603
x:	1.158970386539	0.203814501730	0.203814581037	0.203814561328	0.000000019709	-0.000000059597
x:	1.190056245939	0.196507285750	0.196507364511	0.196507345350	0.000000019161	-0.000000059600
x:	1.221750217779	0.189138515593	0.189138561487	0.189138575189	-0.000000013702	-0.000000059596
x:	1.254138569173	0.181705027166	0.181705087423	0.181705086768	0.000000000655	-0.000000059602
x:	1.287320295169	0.174202711977	0.174202784896	0.174202771576	0.000000013320	-0.000000059599
x:	1.321418432469	0.166624545576	0.166624620557	0.166624605173	0.000000015384	-0.000000059598
x:	1.356585716292	0.158960217743	0.158960267901	0.158960277339	-0.000000009438	-0.000000059596
x:	1.393018722519	0.151194300960	0.151194363832	0.151194360555	0.000000003277	-0.000000059595
x:	1.414213562373	0.146762652495	0.146762669086	0.146762663174	0.000000005913	-0.000000010679
x:	0.065896761049	0.398076980336	0.398077040911	0.398077039931	0.000000000979	-0.000000059595
x:	0.113411555833	0.396384819146	0.396384894848	0.396384878748	0.000000016100	-0.000000059601
x:	0.155068672183	0.394174398848	0.394174486399	0.394174458446	0.000000027952	-0.000000059598
x:	0.193392483833	0.391551192645	0.391551256180	0.391551252249	0.000000003931	-0.000000059604
x:	0.229466279456	0.388576167409	0.388576239347	0.388576227007	0.000000012340	-0.000000059598
x:	0.263888271986	0.385290687187	0.385290741920	0.385290746785	-0.000000004864	-0.000000059597
x:	0.297033228393	0.381725674206	0.381725728512	0.381725733800	-0.000000005288	-0.000000059593
x:	0.329159950016	0.377905230684	0.377905279398	0.377905290287	-0.000000010889	-0.000000059603
x:	0.360453699018	0.373849440845	0.373849511147	0.373849500448	0.000000010698	-0.000000059604
x:	0.391055896896	0.369575196048	0.369575262070	0.369575255651	0.000000006419	-0.000000059603
2 ²⁴ Accuracy						0.000000059605

Table 18. Comparison between SRC macro and NFG; numeric function $\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$,
 $N=1,000,000$ and $\varepsilon = 2^{-24}$.

2. Fixed Point Implementation

As mentioned before, the advantage of using fixed point is the reduction in hardware and the reduced pipeline depth. The disadvantage is that it takes more work to program.

Macros may be used to define certain behavior that is easier to describe in HDL or to provide special functionality that is not available in regular programming. In the NFG, the multiplier is limited by the 64 bit architecture. The product of two 64 bit

numbers does not give the user access to all 128 bits in the product. HDL can be used to manipulate and access the desired bits.

a. No Macro Multiplier (non-uniform)

The fixed point implementation without a macro is exactly the same as the fixed point implementation with only one exception; the indexing in non-uniform segmentation is accomplished using the user callable macro, priority selector, available in the SRC.

```
#####
#####              INNER LOOP SUMMARY              #####
loop on line 46:
    clocks per iteration:      1
    pipeline depth:           28
#####
#####              PLACE AND ROUTE SUMMARY              #####
Number of Slice Flip Flops:      8,283 out of 67,584    12%
Number of 4 input LUTs:         12,331 out of 67,584    18%
Number of occupied Slices:      11,256 out of 33,792    33%
Number of MULT18X18s:           30 out of 144           20%
freq = 100.2 MHz
#####
```

Table 19. Pipeline depth, place and route summary for $\sqrt{-\ln(x)}$, $N=1,000,000$ and $\varepsilon = 2^{-24}$.
Non-uniform segmentation using priority selector macro.

b. Macro Multiplier Implementation

The goal is to build a multiplier in VHDL or Verilog that can successfully multiply in two's complement and provide a result that is already shifted into the number system chosen for fixed point. Specifically, we want a product that is 32 bits integer and 32 bits fraction.

Several multipliers were built. The multipliers function correctly in simulation on PC's using Xilinx ISE, Project Navigator and Modelsim simulating software. However, when the VHDL or Verilog files were compiled on the SRC, the products were not correct. This version was implemented, but it did not produce correct products.

Appendix B shows the VHDL code for a 32x32 bit multiplier with a 32 bit product. The design instantiates the 18x18 signed multiplier primitive. The design makes use of a modified I/O pipeline design from a Xilinx application note [22].

Appendix B also shows the Verilog file for a 64x64 bit multiplier with a 64 bit product. The 64x64 bit multiplier makes use of the source code for the 64x64 bit multiplier macro designed by SRC.

C. SOURCES OF ERROR

The floating point implementation has only errors associated with the MATLAB computed values and the restrictions placed on ε . When implemented in the SRC, double precision accurately represents what is expected from the values fed into the NFG and the coefficients table.

The fixed point implementation had errors due to several reasons. We explore some of those reasons for error in the NFG as a whole.

1. Function Approximation

Both floating point and fixed point have to work with approximation error. This is discussed in detail in section II B (Segmentation).

2. Absence of Rounding in the Multiplier

The fixed point implementation of the NFG shifts binary bits and truncates lower and upper bits. This introduces error in computing the products and these errors propagate to the final answer.

3. Insufficient Bits

Insufficient bits to represent the full product means that the numbers have to be shifted and truncated. This limits the ability for the NFG.

D. SUMMARY

The NFG implementation of the uniform segmentation using floating point number system has a pipeline depth of 84 or 98 depending on whether the begin point of the domain interval is zero or non-zero (zero is preferred). This implementation must read a memory file containing the polynomial coefficients into OBM. Aside from these requirements, the NFG implemented in uniform segmentation and floating point number systems, provides advantages over using the available user callable macros and the math operators. It can be implemented in very high precision, shorter pipeline depth and in some cases less hardware.

Another advantage of the uniform segmentation is that once compiled, the NFG can compute any of the 15 functions. The memory file with the coefficients must be available.

The NFG non-uniform implementation has a shorter pipeline depth, but requires much hardware to implement the segment index encoder. The segment index encoder is limited to approximately 150 segments in this design. Depending on the function, the precision can be increased as long as the number of segments does not exceed approximately 150.

The fixed point implementation requires a rounding macro and a good macro multiplier to provide the desired product bits and make it effective. However, it provides a significantly smaller pipeline depth than the floating point implementation.

A real advantage of the NFG is when very complicated numeric functions need to be implemented; the NFG has a constant pipeline depth unlike the more complicated functions that have long pipeline depths.

More research is required to realize a complete NFG design. Section VI discusses some suggestions for future work.

VI. CONCLUSION

A. SUMMARY OF WORK

An efficient and fast segmentation of numeric functions was accomplished in MATLAB. Table 20 shows the number of tests (calls to *chebyRemz*) required to segment the suite of 15 functions.

Epsilon = 0.0000000596 = $2^{-24.0}$. N = 1000000			
Function	Interval	%Of tests	# of Segments
2^x	[0,1]	0.00910	35
$1./x$	[1,2]	0.01020	50
\sqrt{x}	[1,2]	0.00750	24
$1/\sqrt{x}$	[1,2]	0.00720	36
$\log_2(x)$	[1,2]	0.00900	44
$\log(x)$	[1,2]	0.00780	39
$\sin(\pi x)$	[0,1/2]	0.01990	58
$\cos(\pi x)$	[0,1/2]	0.01740	58
$\tan(\pi x)$	[0,1/4]	0.01240	58
$\sqrt{-\log(x)}$	[1/512,1/4]	0.04070	163
$\tan(\pi x)^{...}$	[0,1/4]	0.02180	79
$-(x \log_2(x))^{...}$	[1/256,1-1/256]	0.04710	183
$1/(1+\exp(-x))^{...}$	[0,1]	0.00920	20
$(1/\sqrt{2 \cdot p})^{...}$	[0, $\sqrt{2}$]	0.01670	45
$\sin(\exp(x))$	[0,2]	0.07810	265

Table 20. Speed-up in computation time for 15 functions (expressed as a percentage of the time needed when the domain is divided into 1,000,000 points) for $\varepsilon = 2^{-24}$

The NFG circuit built in the SRC was very effective in floating point. The computation of numeric functions in the NFG was shown to obtain accuracy of up to 33 bits. Higher accuracy is possible at the cost of increasing the size of the memory files required to store the coefficients.

Floating point implementation was easier to build on the SRC than the fixed point implementation. However, floating point implementation takes up a large amount of FPGA resources.

The NFG is a useful technique to compute complicated numeric functions that would otherwise require a combination of several other arithmetic operations. The more demanding the numeric function the more reason to use the NFG instead. The NFG is more efficient in 10 out of the 15 functions that were investigated in this thesis (when using the non-uniform segmentation).

The fixed point implementation did not produce all of the desired results. The multiplication required more programming than the floating point implementation required, but the results had errors due to rounding and truncating the intermediate and final results. This area needs more research to improve. The advantage of fixed point implementation is that it requires much less hardware than floating point and therefore can reduce the pipeline depth to about 30% of the pipeline depth required by the floating point implementation.

B. SUGGESTED FUTURE WORK

1. Hybrid of Uniform and Non-Uniform Segmentation

Uniform segmentation is much faster and less complicated than non-uniform segmentation. Although non-uniform segmentation may not be practical on its own, a hybrid of non-uniform and uniform segmentation would take advantage of the strengths of each.

Consider a numeric function that is not suitable for uniform segmentation, such as $\sqrt{-\ln(x)}$, which appears in Figure 4 to demonstrate this fact. In the non-uniform segmentation of the same function; such as Figure 2, the restricting portion is the beginning of the segment. Therefore to capture the most restricting part of the numeric function, segment the numeric function into a few non-uniform segments.

A good starting point is to determine an upper limit for the total number of constant segments. Let us decide on 400 segments. If we dedicate 100 constant segments to the first portion of the numeric function $\sqrt{-\ln(x)}$, then change the segment size for another 100 constant segments and repeat this process four or five times, we will have five non-uniform segments each containing a set of uniform segments.

This method would provide three advantages:

1. Relieve the segmentation constraint from the most restricting segment.
2. The segment index encoder would be small (5 groups of segments) and save FPGA space.
3. The indexing would be less complex once the input has been mapped to the correct group of segments.

2. Expand the Domain of the NFG via Mapping

The functions investigated in this thesis have a limited domain interval. To make the functions useful for a wide range of applications, the domain interval should be increased. Theoretical research is being conducted in this field [21].

3. Build an HDL Multiplier Macro and Tap of Desired Bits

If the multiplier in fixed point were built in a macro, the desired bits could be tapped off. This implementation would be both fast and accurate.

3. Build a Rounding Macro

A macro can be built to round off shifted values in the fixed point implementation instead of truncating the values. This would improve the accuracy in the output of the products and the final result of the NFG.

4. Efficient Segment Index Encoder vice Priority Selector Macros

The priority selectors are fast and work well, but take up a lot of hardware. Combined with the other hardware in the NFG, the priority selectors take up all the resources and limit the accuracy and flexibility of the NFG to handle all the functions. An implementation that uses a more efficient method for the segment index encoder would benefit the NFG.

Sasao, Butler have three suggestions; (1) LUT cascade, (2) Content addressable memory and (3) EVBDD.

5. Different Architecture

If FPGA resources became scarcer and one wanted to implement a larger coefficients table, the only way to make room is to remove the major consumers of real estate. In the NFG, it would be the segment index encoder that is implemented as a priority selector macro and the multipliers. We have already discussed possible solutions to removing large selectors.

Using Horner's rule, a multiplier can be eliminated from the NFG. Equation (0.5) shows how to apply Horner's rule to the NFG.

$$f(x) = c_2x^2 + c_1x + c_0 = (c_2x + c_1)x + c_0 \quad (0.5)$$

The NFG hardware would add one more adder stage, however if the segment index encoder were able to work in one or two clocks, this would be a speed-up from the previous architecture as long as the adder stages take fewer clocks than the multipliers. Floating point adders can take as many clocks as the multipliers, but in two's Complement or signed magnitude, the adders are faster than the multiplier.

In the previous architecture, x^2 takes many more clocks than the segment index encoder and adds to the pipeline depth.

Figure 22 shows an overview of the NFG architecture when Horner's rule has been applied.

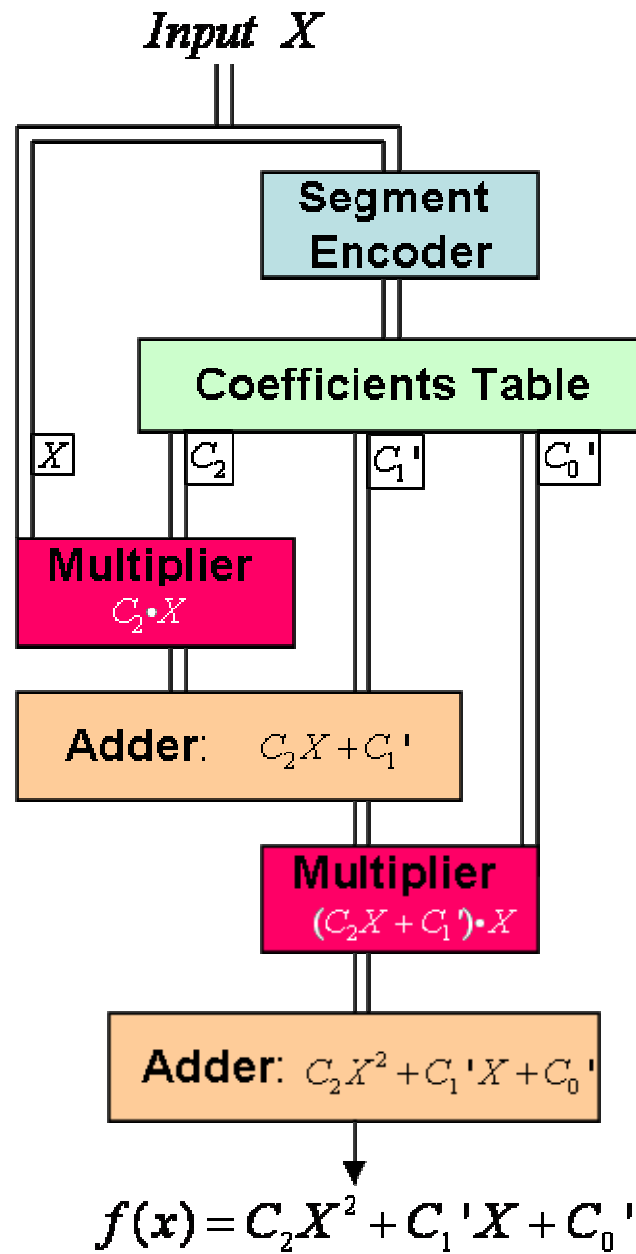


Figure 22. Horner's rule NFG architecture overview.

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APPENDIX A. MATLAB ALGORITHMS

The following MATLAB Code generates the segmentation for any function; however a user interface has been added for convenience. The user simply picks a number instead of re-typing the entire function or the interval for evaluation. The interface limits the MATLAB Code to the suite of functions found in Table 1.

A.1 QUADRATIC APPROXIMATION USING POLYFIT

This code implements the quadratic approximation using the MATLAB function *Polyfit*. There are 6 files needed to run the non-uniform and uniform segmentation: *QuadAppxPfit.m*, *multipleQuadApprox.m*, *varQuadApprox.m*, *dec2binfp.m*, *constantQuadApprox.m*, and *constQuadAppxWErr.m*.

QuadAppxPfit.m is the top function where the program starts and ends. All the other files are child functions that provide the segmentation data back to this file for presentation / file storage.

multipleQuadApprox.m calls the non-uniform segmentation algorithms to collect the data for the segment endpoints and coefficients.

varQuadApprox.m tests proposed segments and reduces finds the optimum width of the segment by testing the approximation error to ε .

dec2binfp.m is the file that converts decimal numbers into binary. This is limited to converting one integer value and only up to 9 binary bits of accuracy.

constantQuadApprox.m is used for uniform segmentation when the number of segment is known before hand. The key requirement is to input the number of segments desired, the approximation error is unspecified.

constQuadAppxWErr.m needs to have ε specified, then this file will compute the uniform segmentation of the numeric function that meets the constraint ε .

FILE: QuadAppxPfit.m

```
% Arbitrary_PW_Quadratic_Approx.m
% Created: January 6, 2006 (from Arbitrary_PW_Linear_Approx.m)
% Last modified: October 20, 2006
% Produced by: Tom Mack & Jon Butler
% Modified by: Njuguna Macaria for quadratic approximation
%
% This program produces a segmentation of a given function using either:
%     1. Uniform piecewise Quadratic approximation
%     2. Non-uniform piecewise Quadratic approximation
%     3. Both
%
% It is based on the algorithm:
%     1. For non-uniform, the MATLAB polyfit function
%     2. For uniform, dividing the range of the input into
%         equal, user-defined segments
%         or by using max error to determine max segment length
%         at the greatest curvature and then dividing the range
%         up into equal segments.
%         All with intercept shifting to balance the positive
%         and negative error
%
% Inputs
%     N - number of elements on which function is expressed
%     f(x) - function to be evaluated
%     x_low - low end of interval over which f(x) is evaluated
%     x_high - high end of interval over which f(x) is evaluated
%     epsilon - precision of approximation (for variable only)
%     consegs - number of segments to use to approximate (constant only)
%
% Outputs
%     Segment info - Segment #, Begin Pt, End Pt, Coefficients, & Error
%     Plot showing the approximation
%     Text file used to initialize memory in SRC (both Binary & Decimal)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INPUT OF USER-SPECIFIED PARAMETERS %%%%%%%%%%
clear
close all
format long g
fprintf('\n')
fprintf('\n*****')
fprintf('\n')
fprintf('\n      QUADRATIC APPROXIMATION OF A FUNCTION USING POLYFIT ')
fprintf('\n')
fprintf('\n')
%% Get FUNCTION to be approximated (user input)
func = input( 'Input the Function, func[sqrt(-1*log(x))]: ', 's');
if isempty(func)
    func = 'sqrt(-1*log(x))'; %% default
end

%% Get LOW range (user input)
x_low = input( 'Input the Lower Range of x - LOW value, x(low)[1/256]: ');
if isempty(x_low)
    x_low = 1/256; %% default
```

```

end

%% Get HIGH range (user input)
x_high = input( 'Input the Higher Range of x - HIGH value, x(high)[1/4:]');
if isempty(x_high)
    x_high = 1/4;          %% default
end

%% Get CONSTANT OF VARIABLE segmentation (User input)
vari_or_const = 0;
while vari_or_const ~= 1 && vari_or_const ~= 2 && vari_or_const ~= 3
    vari_or_const = ...
        input( '(1)Non-uniform (2)Uniform Segmentation or (3)Both [1:]');
    if isempty(vari_or_const)
        vari_or_const = 1;    %% default Non-uniform
    end
end

%% If non-uniform segmentation, then enter ERROR parameters
if vari_or_const ~= 2
    epsilon = input( 'Input the Desired Error, epsilon[0.0001]: ');
    if isempty(epsilon)
        epsilon = 0.0001;    %% default
    end
end

%% If uniform segmentation, find how the user will restrict # of segments
if vari_or_const == 2
    err_or_segs = ...
        input( 'Constrain by (1)Number of Segments or (2)Error [1]: ');
    if isempty(err_or_segs)
        err_or_segs = 1;    %% default
    end
    if err_or_segs == 1
        consegs = input( 'Input the number of Desired Segments[100]: ');
        if isempty(consegs)
            consegs = 200;    %% default
        end
    end
    if err_or_segs == 2
        epsilon = input( 'Input the Desired Error, epsilon[0.0001]: ');
        if isempty(epsilon)
            epsilon = 0.0001;    %% default
        end
    end
end

N = input( 'Input the no. of pts the fct is to be evaluated; N[10000]: ');
if isempty(N)
    N = 10000;    %% default
end

% eqn = input( 'Input the equation to use:
%             (1)F(x)=ax^2+bx+c or (2)F(x)=a(x-p)^2+b(x-p)+c, [1]: ');
% if isempty(eqn)

```

```

% eqn = 1;                                %% default
%end

eqn = 1;

%%% Based on the number of points to be used for the curve, find the
%%% x values to calculate and spread over the approximating function
N = N * (x_high - x_low);
x = linspace(x_low, x_high, N);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% NOTES %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The segments in this program do NOT overlap (i.e. the first element of
% the NEXT segment is NOT the last element of the LAST segment.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

eval(['F = ', func, ';'])    % Evaluate the function and place values in F

%Print demarcation line
fprintf('\n*****')
fprintf('\n')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Segmentation Algorithm %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% REPEAT FOR EACH i %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
repeat = 1;
while repeat == 1
    if (mod(vari_or_const,2) == 1)
        [endpt,seg_end_point,c_2,c_1,c_0] = multipleQuadApprox(x,F,epsilon);
    end
    if (vari_or_const == 2) && (err_or_segs == 1)
        [endpt,seg_end_point,c_2,c_1,c_0] = constantQuadApprox(x,F,consegs);
    end
    if ((vari_or_const == 2) && (err_or_segs == 2)) || (vari_or_const == 4)
        [endpt,seg_end_point,c_2,c_1,c_0] = constQuadAppxWErr(x,F,epsilon);
    end

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Compute and plot function, approximate function and error
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    ind = 1;                                % Index for each segment
    for i = 1:length(seg_end_point);
        m = 1;                                % Index within each segment
        XP = [];
        FP = [];
        Error = [];
        while (ind < seg_end_point(i))
            XP(m) = x(ind);
            FNC(m) = F(ind);                    % Actual function (Fct No correction)
            FP(m) = c_2(i)*((x(ind)).^2)+c_1(i)*x(ind) + c_0(i); % Approx
            Error(m) = FNC(m) - FP(m);
            ind = ind + 1;
            m = m + 1;
        end %while

        MaxError(i) = max(abs(Error));          % Keep track of all errors
    end
end

```

```

if (mod(i,2) == 0) % Plot every other segment a different color
    figure(mod(vari_or_const,2)+1)      %% Blue
    plot(XP,FP)
    figure(mod(vari_or_const,2)+3)      %% Blue
    plot(XP,Error)
else
    figure(mod(vari_or_const,2)+1)
    plot(XP,FP,'r','LineWidth',2)      %% Red
    figure(mod(vari_or_const,2)+3)
    plot(XP,Error,'r','LineWidth',2)   %% Red
end %if (mod(i,2) == 0)
figure(mod(vari_or_const,2)+1)
hold on
xlabel('x','FontSize',10)
ylabel('f(x)','FontSize',10)
if (mod(vari_or_const,2) == 1)
    title(['NON-UNIFORM f(x) segmentation. No. of segments = ',...
        num2str(length(seg_end_point)),'.'],'FontSize',10)
elseif (mod(vari_or_const,2) == 0)
    title(['UNIFORM f(x) segmentation. No. of segments = ',...
        num2str(length(seg_end_point)),'.'],'FontSize',10)
end
figure(mod(vari_or_const,2)+3)
hold on
xlabel('x','FontSize',14)
% Pick the maximum error from all the segments
ylabel(['Error(x). Max Error = ',num2str(max(MaxError)),'.'],...
    'FontSize',10)
if (mod(vari_or_const,2) == 1)
    title(['Error for NON-UNIFORM f(x) segmentation. No. of segs = ',...
        num2str(length(seg_end_point)),'.'],'FontSize',10)
elseif (mod(vari_or_const,2) == 0)
    title(['Error for UNIFORM f(x) segmentation. No. of segs = ',...
        num2str(length(seg_end_point)),'.'],'FontSize',10)
end
end %for i = 1:length(seg_endpt)
figure(mod(vari_or_const,2)+1)
plot(x,F) % Plot function on same figure as piecewise approximation
stem(x(seg_end_point),F(seg_end_point))
hold off

%%%%%%%%%   Decimal to Binary Conversion Algorithm   %%%%%%%%%%%%%%%
% Convert string end points, c_1 and c_0 into a binary string with 1
% integer bit and 8 fraction bits and print results table.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (mod(vari_or_const,2) == 1)
    fprintf('\n NON-UNIFORM Segmentation')
elseif (mod(vari_or_const,2) == 0)
    fprintf('\n UNIFORM Segmentation')
end
if eqn == 1
    fprintf('\n Segment      End Point      End Point      c_2      ',...
        'c_2              c_1          c_1          c_0      ',...
        'c_0')
    fprintf('\n Number      (Decimal)      (Binary)      (Decimal)',...

```

```

        '(Binary)          (Decimal)  (Binary)          ',...
        '(Decimal)  (Binary)')
end

for i = 1:length(seg_end_point)
    xbin(i)      = dec2binfp(x(seg_end_point(i)));
    segment(i+1) = x(seg_end_point(i));    % Used in next program
    c_2bin(i)     = dec2binfp(c_2(i));
    c_1bin(i)     = dec2binfp(c_1(i));
    c_0bin(i)     = dec2binfp(c_0(i));
    if eqn == 1
        % Print Remaining Results Table
        fprintf('\n      %3d      %8.6f      %019.9f %10.5f      %019.9f ',...
            '%10.5f      %019.9f %10.5f      %019.9f', i-1, ...
            x(seg_end_point(i)), xbin(i), c_2(i), c_2bin(i), c_1(i),...
            c_1bin(i), c_0(i), c_0bin(i))
    end % if eqn == 1
end %for i = 1:length(seg_end_point)

% Create text file of Binary values to initialize memory
memBin = [c_2bin .* 10^9; c_1bin .* 10^9 ; c_0bin .* 10^9]; % Memory with
bin
fid      = fopen('memory.mem','w');
fprintf (fid, '\n%018.0f%018.0f%018.0f', memBin);
fclose (fid);

% Create text file of Decimal Values to initialize memory
fid      = fopen('memDEC.mem','w');
format long g;
fprintf(fid, '%5d', length(seg_end_point));          % Number of Segments
memDEC = [segment(2:end); c_2; c_1; c_0]
fprintf(fid, '\n%18.12f %18.12f %18.12f %18.12f', memDEC);
fclose (fid);

%End text file creation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if eqn == 2
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% The following created from:  Extract_PL_Params.m
    %
    % This program extracts from the segmentation and the function, the
    %      1. Squared term coefficient
    %      2. Linear term coefficient
    %      3. Constant
    %
    %
    % which are the parameters needed to store in the coefficients
    % memory.  It produces the BINARY values of these parameters.
    %
    % The segmentation occurs as a vector of end points.
    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    fprintf('\n')

fprintf('\n*****')

```

```

fprintf('\n')
segment(1) = 0;
for i = 1:length(segment)
    seg_index(i) = floor(N*segment(i)/(x_high-x_low))+1;
end %for i = 1:length(segment)
seg_index;
for i = 2:length(segment)
    slope(i-1) = (F(seg_index(i)-1) - F(seg_index(i-1)))/...
                (x(seg_index(i)-1) - x(seg_index(i-1)));
    intercept(i-1) = F(seg_index(i)-1) - slope(i-1)*x(seg_index(i)-1);
    a = max(F(seg_index(i-1):seg_index(i)-1) ...
            - (slope(i-1).*x(seg_index(i-1):seg_index(i)-1)...
            + intercept(i-1) ) );
    b = min(F(seg_index(i-1):seg_index(i)-1) ...
            - (slope(i-1).*x(seg_index(i-1):seg_index(i)-1)...
            + intercept(i-1) ) );
    error(i-1) = 0.5*(a + b); %YES, it is a + b.
    intercept(i-1) = intercept(i-1) + error(i-1) + slope(i-1)*segment(i-
1);

    s_m_e(i-1) = segment(i) - segment(i-1);
    clx(i-1) = s_m_e(i-1)*slope(i-1);
    approx(i-1) = clx(i-1) + intercept(i-1);
    exact(i-1) = 2^segment(i); %Exact value of f(x) at end of
segment.
end %for i = 2:length(segment)
fprintf('\nDECIMAL values for Approx = slope*(x - pivot) + intercept.')
fprintf('\nseg no. [s, e] slope intercept ',...
        'pivot approx_error e-s (e-s)*slope (e-s)',...
        '*slope+intercept exact f(x)\n')
for i = 1:length(segment)-1
    fprintf('%1.0f [%8.6f %8.6f] %8.6f %8.6f %8.6f %8.6f',...
            '%8.6f %8.6f %8.6f %8.6f \n', i-1, segment(i),...
            segment(i+1), slope(i), intercept(i), segment(i), error(i),...
            s_m_e(i), clx(i), approx(i), exact(i))
end %for i = 1:length(segment)-1
%hold on
%plot(x(1:N),slope(1).*x(1:N)+intercept(1))
%Convert s, e, slope, intercept, and pivot to binary.
fprintf('\nBINARY values')
fprintf('\nseg no. [s, e] slope intercept',...
        'approx_error e-s (e-s)*slope (e-s)*sl+intercept exact
f(x)\n')
for i = 1:length(segment)-1
    digits = ceil(log2(length(segment)-1));
    s_seg_no = dec2bin(i-1,digits);
    s_s(i) = dec2binfp(segment(i));
    s_e(i) = dec2binfp(segment(i+1));
    s_slope(i) = dec2binfp(slope(i));
    s_intercept(i) = dec2binfp(intercept(i));
    if error(i) < 0;
        error(i) = abs(error(i));
    end % if error(i) < 0;
    s_error(i) = dec2binfp(error(i));
    s_s_m_e(i) = dec2binfp(s_m_e(i));
    s_clx(i) = dec2binfp(clx(i));

```



```

        s_approx(i) = dec2binfp(approx(i));
        s_exact(i)  = dec2binfp(exact(i));
        fprintf('%s [%10.8f %10.8f] %10.8f %10.8f %10.8f %10.8f',...
            '%10.8f %10.8f %10.8f \n', s_seg_no, s_s(i), s_e(i), ...
            s_slope(i), s_intercept(i),s_error(i),s_s_m_e(i), ...
            s_clx(i), s_approx(i), s_exact(i))
    end %for i
end % if eqn == 2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    fprintf('\n')
    fprintf('\n*****')
    fprintf('\n')
    if vari_or_const ~= 3
        repeat = 0;
    end
    if vari_or_const == 3
        vari_or_const = 4;
    end
end % while repeat = 1
% End file: QuadAppxPfit.m

```

FILE: multipleQuadApprox.m

```
function [endpt,indx,c2,c1,c0] = multipleQuAdapprox(x,fct,max_error)

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function will produce multiple Quadratic-line approximations of a
% given function to within the bounds of max error provided.
% Created by Tom Mack for linear approximations
% Created: Mar 31, 2006
%
% Modified for Quadratic approximations by Njuguna Macaria
% Modified: Dec 30, 2006
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

i      = 1;
indx   = 1;
seg_no = 1;
endpt  = [];
c2     = [];
c1     = [];
c0     = [];

while i < length(fct)
    [endpt(seg_no),indx(seg_no),c2(seg_no),      c1(seg_no),c0(seg_no)] =
    varQuadApprox(x,fct,max_error,i);
    i      = indx(seg_no) + 1;
    seg_no = seg_no      + 1;
end
```

FILE: varQuadApprox.m

```
function [endpt,i,c2,c1,c0] = varQuadApprox(x,fct,max_error,indx)
% This function creates a 2nd Order approximation of a given function
% using the polyfit function. It continues to calculate polyfits until
% maximum error is exceeded.
% Linear approximation Created by Tom Mack >> Mar 31, 2006
%
% Modified for Quadratic approximation by Njuguna Macaria
% Modified: Dec 29, 2006

for i=indx:length(fct);
    p = polyfit(x(indx:i),fct(indx:i),2); % Fit equ to 2nd order poly
    c_2(i) = p(1); % Coefficient of X^2
    c_1(i) = p(2); % Coefficient of X
    c_0(i) = p(3); % Intercept of polynomial

    approx(indx:i) = p(1)*(x(indx:i)).^2 + p(2)*x(indx:i) + p(3);
    errors = approx(indx:i) - fct(indx:i);
% % maxposerror = max(errors);
% % maxnegerror = min(errors);
% % % c_0delta(i) = abs((abs(maxposerror) - abs(maxnegerror))/2);
% %
% % % If the negative error is bigger, then the delta should be negative
% % % if abs(maxnegerror) > abs(maxposerror)
% % % c_0delta(i)= -1 * c_0delta(i);
% % % end % if

% % % approx(indx:i) = approx(indx:i) - c_0delta(i);
% % % errors = approx(indx:i) - fct(indx:i);
error = max(abs(errors));

% If exceeded the max error, then go back to the previous endpoint
if error > max_error
    i = i-1;
    endpt = x(i);
    c2 = c_2(i);
    c1 = c_1(i);
    c0 = c_0(i);
    return
end % if error > max
end % for i=indx+1:length(fct)

endpt = x(i);
c2 = c_2(i); % Removed i = i-1;
c1 = c_1(i);
c0 = c_0(i);
```

FILE: dec2binfp.m

```
function [binfp] = dec2binfp(x,n)
% This function converts a decimal number to a fixed point binary number
% with one integer followed by n points to the right of the decimal
%
% Created by Tom Mack
% Last modified: August 22, 2006
%
% Inputs
%   x = decimal number to be converted (does not have to be an integer)
%   n (optional, default 9) = bit resolution to the right and left of decimal pt
% Outputs
%   binfp = binary floating point representation
%   Negative inputs are output in 18-bit (9.9) format
%
if nargin < 2, n = 9; end
if isnan(x) == 1,
    binfp = NaN;
    return
elseif x == Inf
    binfp = Inf;
    return
elseif x < 0,
    x = (x * 2^n) + 2^(2*n);
    x = dec2bin(x,18);
    x = str2double(x);
    x = x / 10^n;
    binfp = x;
    return
else
    x = x * 2^n;
    x = dec2bin(x,18);
    x = str2double(x);
    x = x / 10^n;
    binfp = x;
end
```

FILE: constQuadAppxWErr.m

```
function [endpt,indx,c2,c1,c0] = constQuadAppxWErr(x,fct,max_error)

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function will produce multiple Quadratic-line approximations of a
% constant size of a given function to within the bounds of the
% max error provided. Coefficients & intercept calculated using polyfit.
% Intercept adjusted to balance max positive and negative errors.
% Created by Tom Mack for linear approximations
% Created: July 10, 2006
% Modified: July 11, 2006
% Modified again by Njuguna Macaria for Quadratic approximations
% Modified: Dec 30, 2006
%
% Compute # of segs
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

firstderiv = diff(fct)./diff(x);
secndderiv = diff(firstderiv)./diff(x(1:length(firstderiv)));
[dermax,i] = max(abs(secndderiv));
error      = 0;
loop_stop  = 0;
i_low      = i - 1;

if i_low <= 0
    i_low = 1;
end

i_high = i + 1;

if i_high > length(fct)
    i_high = length(fct);
end

% If error is too small, increase until just under the max error
% This gives the max size of the segment within the desired error
while error < max_error || loop_stop < length(fct)
    i_low = i_low - 1;
    if i_low <= 0
        i_low = 1;
    end
    i_high = i_high + 1;
    if i_high > length(fct)
        i_high = length(fct);
    end

    % Get coefficients, approximate function and find error
    % Adjust function based on the error (move it up or down)
    p = polyfit(x(i_low:i_high),fct(i_low:i_high),2);
    approx(i_low:i_high) = p(1)*(x(i_low:i_high)).^2 + ...
        p(2)*x(i_low:i_high) + p(3);
    errors = approx(i_low:i_high) - fct(i_low:i_high);
    maxposerror = max(errors);
    maxnegerror = min(errors);
    c_0delta = abs((abs(maxposerror) - abs(maxnegerror))/2);
```

```

% Figure out if the error is positive or negative and move the function
% to compensate and balance the error of the approximated function
if abs(maxnegerror) > abs(maxposerror)
    c_0delta = -1 * c_0delta;
end % if

% Re-check the error and find the max error
approx(i_low:i_high) = approx(i_low:i_high) - c_0delta;
errors                = approx(i_low:i_high) - fct(i_low:i_high);
error                 = max(abs(errors));

% If error is larger than should be
if error > max_error
    i_low = i_low + 1;
    i_high = i_high - 1;
end
loop_stop = loop_stop + 1;
end
segszsize = i_high - i_low;
consegs = ceil(length(fct)/segszsize);

%
% Determine Coefficients of segments
%
idx=1;
for i = 1:consegs
    indx(i) = round((length(x)/consegs)*i);
    if indx(i) == 0
        indx(i) = 1;
    end
    if i==consegs
        indx(i) = length(x);
    end
    endpt(i) = x(indx(i));
    p        = polyfit(x(indx:i),fct(indx:i),2);
    approx(indx:i) = p(1)*(x(indx:i)).^2 + ...
        p(2)*x(indx:i) + p(3);
    errors      = approx(indx:i) - fct(indx:i);
    maxposerror = max(errors);
    maxnegerror = min(errors);
    c_0delta    = abs(abs(maxposerror) - abs(maxnegerror))/2;
    if abs(maxnegerror) > abs(maxposerror)
        c_0delta = -1 * c_0delta;
    end % if
    c2(i) = p(1);
    c1(i) = p(2);
    c0(i) = p(3) - c_0delta; % Constant shift to balance pos & neg error
    idx   = indx(i)+1;
    i     = i+1;
end
end

```

FILE: constantQuadApprox.m

```
function [endpt,indx,c2,c1,c0] = constantQuadApprox(x,fct,constsegs)
%
% This function will produce multiple Quadratic line approximations of a
% given function to within the bounds of the number of segments provided.
% Coefficients calculated by polyfit. Intercept adjusted to balance
% maximum positive and negative errors.
%
% Created by Tom Mack for linear approximations
% Created: June 4, 2006
% Modified for Quadratic approximations by Njuguna Macaria
% Modified: July 11, 2006
%

indx=1;

for i = 1:constsegs
    indx(i) = round((length(x)/constsegs)*i);
    if i==constsegs
        indx(i) = length(x);
    end
    endpt(i) = x(indx(i));
    p = polyfit(x(indx:indx(i)),fct(indx:indx(i)),2);

    approx(indx:indx(i)) = p(1)*(x(indx:indx(i))).^2+p(2)*x(indx:indx(i))+p(3);
    errors = approx(indx:indx(i)) - fct(indx:indx(i));
    maxposerror = max(errors);
    maxnegerror = min(errors);
    c_0delta = abs((abs(maxposerror) - abs(maxnegerror))/2);

    if abs(maxnegerror) > abs(maxposerror)
        c_0delta = -1 * c_0delta;
    end % if
    c2(i) = p(1);
    c1(i) = p(2);
    c0(i) = p(3)- c_0delta; % Intercept shift to balance pos & neg error
    indx = indx(i)+1;
    i = i+1;
end
```

A.2 QUADRATIC APPROXIMATION USING REMEZ ALGORITHM

The thesis was designed using the *Remez* algorithm. The following files were developed to compute the segmentation. The top level file is *QuadAppxRemz.m*, which calls a set of user written MATLAB functions to display and request the user input (*UserInput.m*), obtain the numeric functions selected by the user and their respective domain intervals (*getF.m*) and then compute the segmentation.

Non-uniform segmentation was performed by *multipleQuadApprox.m* in conjunction with *varQuadApproxHyb3AvgThird.m* and *chebyRemz.m*. *chebyRemz.m* takes place of *Polifit.m* that is an optimized user callable MATLAB function shown in A.1 above.

Uniform segmentation is performed by two other files. If the number of segments is known without explicit input of ε , then *constantQuadApprox.m* is the file that is used. If on the other hand, ε is defined and uniform segmentation is desired, then *constQuadAppxWErr.m* is the file that is used.

The file *twosComp.m* was developed to convert the data to a two's complement, fixed point binary, hexadecimal or decimal number. Note the two's complement decimal number is not the same as a float or double data type.

FILE: QuadAppxRemz.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% QuadAppxRemz.m
% Created: January 6, 2007
% Created by: Njuguna Macaria
% Last modified: Auguse 3, 2007
% Modified by: Njuguna Macaria
%
% This program produces a segmentation of a given function using either:
% 1. Uniform Quadratic approximation
% 2. Non-uniform piecewise Quadratic approximation
% 3. Both
%
% It is based on the algorithm:
% 1. For non-uniform, the MATLAB Remez algorithm
%
% 2. For uniform, dividing the range of the input into
% equal, user-defined segments
% or by using max error to determine max segment length
% at the greatest curvature and then dividing the range
% up into equal segments.
%
% Inputs
% Inputs are taken from an input function; "userInput();"
% N - number of elements on which function is expressed
% eqn - (1)F(x)=ax^2+bx+c OR PIVOT: (2)F(x)=a(x-p)^2+b(x-p)+c
% x_low - low end of interval over which f(x) is evaluated
% x_high - high end of interval over which f(x) is evaluated
% func(x) - function to be evaluated
% epsilon - precision of approximation (for variable only)
% conseqs - number of segments to use to approximate (constant only)
% err_or_segs - Constant segmentation; decide # of segments or err bound
% vari_or_const - Variable or constant segmentation
%
% Outputs
% Segment info - Segment #, Begin Pt, End Pt, Coefficients, & Error
% Plot showing the approximation
% Text file used to initialize memory in SRC (both Binary & Decimal)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% INPUT OF USER-SPECIFIED PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear
clc
close all
format long g;

% Get user input
% profile on % For use when debugging. Find runtimes
sel = userInput();
[f,interval,vari_or_const,err_or_segs,conseqs,epsilon,N]=getF(sel);

%% Based on the number of points to be used for the curve, find the
%% x values to calculate and spread over the approximating function

syms x

```

```

eval(['func = ', f, ';'])
eval(['intv = ', interval, ';'])
x_pts = linspace(intv(1), intv(2), N);
vecFunc = inline(vectorize(func)); %Vectorized version of func.
y_actual = vecFunc(x_pts); %Evaluate the function with x_pts

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% NOTES %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% The segments in this program overlap (i.e. the first element of
% the NEXT segment IS the last element of the LAST segment.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Print demarcation line
fprintf('\n*****\n')
fprintf('\n')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Segmentation Algorithm %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
repeat = 1;
while repeat == 1
    if (mod(vari_or_const,2) == 1)
        [endpt,seg_end_point,c_2,c_1,c_0] = ...
            multipleQuadApprox(x_pts,func,epsilon);
    end
    if (vari_or_const == 2) && (err_or_segs == 1)
        [endpt,seg_end_point,c_2,c_1,c_0] = ...
            constantQuadApprox(x_pts,vecFunc,consegs);
    end
    if ((vari_or_const == 2) && (err_or_segs == 2)) || (vari_or_const == 4)
        [endpt,seg_end_point,c_2,c_1,c_0] = ...
            constQuadAppxWErr(x_pts,func,epsilon);
    end

    fprintf('\n*****\n')
    fprintf('\n\nBack from all the Segmentation\n\n')
    fprintf('\n*****\n')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Compute and plot function, approximate function and error
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for i = 1:length(seg_end_point)-1;

        % looking at each segment find the approximate and actual points
        XP = x_pts(seg_end_point(i):seg_end_point(i+1));
        c = [c_2(i),c_1(i),c_0(i)];
        FNC = vecFunc(XP);
        FP = polyval(c,XP);
        Error = FP - FNC;

        MaxError(i) = max(abs(Error));
        if (mod(i,100)==0) % Only used when trying to limit graphing
            if (mod(i,2) == 0) % Plot every other segment a different color
                figure(mod(vari_or_const,2)+1) %% Blue
                plot(XP,FP)
                figure(mod(vari_or_const,2)+3) %% Blue
                plot(XP,Error)
            end
        end
    end
end

```

```

else
    figure(mod(vari_or_const,2)+1)
    plot(XP,FP,'r','LineWidth',2)        %% Red
    figure(mod(vari_or_const,2)+3)
    plot(XP>Error,'r','LineWidth',2)    %% Red
end %if (mod(i,2) == 0)
figure(mod(vari_or_const,2)+1)
hold on
xlabel('x','FontSize',10)
ylabel('f(x)','FontSize',10)
if (mod(vari_or_const,2) == 1)
    title([ 'NON-UNIFORM f(x)=',f,...
            ' segmentation. No. of ',...
            'segments = ',...
            num2str(length(seg_end_point)-1),'.'],...
            'FontSize',10)
elseif (mod(vari_or_const,2) == 0)
    title([ 'UNIFORM f(x)=',f,...
            ' segmentation. No. of segments = ',...
            num2str(length(seg_end_point)-1),'.'],...
            'FontSize',10)

end
figure(mod(vari_or_const,2)+3)
hold on
xlabel('x','FontSize',14)
errPwr2 = log2(max(MaxError));
ylabel(['Max Error = ',num2str(max(MaxError)),' = 2\^',...
        num2str(errPwr2),'.'], 'FontSize',10)
if (mod(vari_or_const,2) == 1)
    title([ 'Error for NON-UNIFORM f(x)=',f,...
            ' segmentation. No. of segs = ',...
            num2str(length(seg_end_point)-1),'.'],...
            'FontSize',10)
elseif (mod(vari_or_const,2) == 0)
    title([ 'Error for UNIFORM f(x)=',f,...
            ' segmentation. No. of segs = ',...
            num2str(length(seg_end_point)-1),'.'],...
            'FontSize',10)

end
end % if (mod(i,100)==0) Graphing STOP/START
end %for i = 1:length(seg_endpt)
figure(mod(vari_or_const,2)+1)
plot(x_pts,y_actual) % Plot func on same fig as piecewise approx
stem(x_pts(seg_end_point),y_actual(seg_end_point))
hold off

%%%%%%%%%%      Decimal to Binary Conversion Algorithm      %%%%%%%%%%%

%=====
% Print whether Uniform or Non-uniform %
%=====
if (mod(vari_or_const,2) == 1)
    fprintf('\n NON-UNIFORM Segmentation')
elseif (mod(vari_or_const,2) == 0)
    fprintf('\n UNIFORM Segmentation')

```

```

end

% =====%
% % Convert to Twos Complement (32.32) %
% % and save in a file. %
% =====%
fractLen = 32; % 32 bits to represent the fraction
intLen = 64-fractLen; % 32 bits to represent the integer

% =====%
% % Convert to Twos Complement (16.16) %
% % and save in a file. %
% =====%
% fractLen = 16; % 16 bits to represent the fraction
% intLen = 32 - fractLen; % 16 bits to represent the integer

% =====%
% % BINARY FILE %
% =====%
% % Create text file of Binary values to initialize memory
% fid = fopen('memBIN.mem','w');
% fprintf(fid,'%d', length(seg_end_point)-1); % Number of Segments
%
% % Convert the values to binary and save in the file
% for i = 1:length(seg_end_point)-1
% xbin(i,:) = twosComp(x_pts(seg_end_point(i+1)),intLen, fractLen);
% segmnt(i) = x_pts(seg_end_point(i+1)); % Used in next program
% c_2bin(i,:) = twosComp(c_2(i),intLen, fractLen);
% c_1bin(i,:) = twosComp(c_1(i),intLen, fractLen);
% c_0bin(i,:) = twosComp(c_0(i),intLen, fractLen);
% memBin = [ xbin(i,:), ' ', c_2bin(i,:), ' ', ...
% c_1bin(i,:), ' ', c_0bin(i,:)];
% fprintf (fid, '\n%s', memBin);
% % %
% % % fprintf (fid, '\n', xbin(i,:), ' ', c_2bin(i,:), ...
% % % ' ', c_1bin(i,:), ' ', c_0bin(i,:));
% end %for i = 1:length(seg_end_point)
%
% fclose (fid);

% =====%
% % HEXADEDICMAL FILE %
% =====%
% Create text file of Binary values to initialize memory
fid = fopen('memHEX0x.mem','w');
Num_of_Segments = length(seg_end_point)-1;
fprintf(fid,'%6d', Num_of_Segments); % Number of Segments

% for uniform segmentation, store a step size
if (vari_or_const == 2) || (vari_or_const == 4)
step_len = Num_of_Segments/(intv(2) - intv(1)); %
fprintf(fid, '\n0x%s', twosComp(step_len,intLen, fractLen));
end

```

```

% Convert the values to binary and save in the file
for i = 1:length(seg_end_point)-1
    xbin(i,:) = twosComp(x_pts(seg_end_point(i+1)),intLen, fractLen);
    segmnt(i) = x_pts(seg_end_point(i+1)); % Used in next program
    c_2bin(i,:) = twosComp(c_2(i),intLen, fractLen);
    c_1bin(i,:) = twosComp(c_1(i),intLen, fractLen);
    c_0bin(i,:) = twosComp(c_0(i),intLen, fractLen);
    memBin      = [[ '0x',xbin(i,:)], ' ',...
                   [ '0x',c_2bin(i,:)], ' ',...
                   [ '0x',c_1bin(i,:)], ' ',...
                   [ '0x',c_0bin(i,:)]      ];
    fprintf (fid,'\n%s',memBin);

% %          fprintf (fid,'\n',xbin(i,:), ' ',c_2bin(i,:),...
% %          ' ',c_1bin(i,:), ' ',c_0bin(i,:));
end %for i = 1:length(seg_end_point)

fclose (fid);

%=====
% DECIMAL FILE %
%=====
% Create text file of Decimal Values to initialize memory
fid = fopen('memDEC.mem','w');
fprintf(fid,'%6d', Num_of_Segments); % Number of Segments
% for uniform segmentation, store a step size
if (vari_or_const == 2) || (vari_or_const == 4)
    step_len = Num_of_Segments/(intv(2) - intv(1)); %
    fprintf(fid,'\n%26.18f', step_len); % Step size in Decimal
end
memDEC = [segmnt(1:end); c_2; c_1; c_0]
maxCoef = max(memDEC);
minCoef = min(memDEC);
fprintf(fid,'\n%26.18f %26.18f %26.18f %26.18f',memDEC);
fclose (fid);
%End text file creation

fprintf('\n')
fprintf('\n*****\n')
if vari_or_const ~= 3
    repeat = 0;
end
if vari_or_const == 3
    vari_or_const = 4;
end
% % % profile viewer
% % pr = profile('info');
% % profsave(pr,'profile_results')
end % End while repeat == 1
% % % maxCoef = max(maxCoef) % for debugging to find number range
% % % minCoef = min(minCoef)
% End file: QuadAppxRemz.m

```

A.2.1 Remez Algorithm With Chebyshev Initial Points

FILE: chebyRemz.m

```
function [poly_coeff, oscil, snd_Err] = chebyRemz(fun,interval,order)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% chebyRemz.m
%
% Get chebyshev polynomial on the first iteration. Repeat for Remez
% application; User specifies the fuction to approxiamte.
% This programs turns the function provided into an inline function.
%
% INPUT:
%     f: function entered by user (want to approximate this)
%     However this function cannot be a constant. f must
%     be only one variable. Must use the variable 'x'.
%     order: order of approximation, e.g. 2nd order polynomial
%     interval: range on which to get the coefficients will be
%              approximated on the users function.
%
% OUTPUT:
%     errRemz: error points for the range given
%     poly_coeff: These are the coefficients of the polynomial that
%                 approximates the function.
%     oscil: Oscillations on interval, for second order poly, we
%            want only 2 oscillations. In this case oscillations
%            are the zeroes of the first derivative.
%
% Author:      Njuguna Macaria
% Created:     20 February 2007      Last Modified: 26 MARCH 2007
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%=====
a      = interval(1);
b      = interval(2);
N      = 500;                               % Number of elements per segment
x_pts  = linspace(a,b,N);                   % x axis sample points
y_act  = fun(x_pts);                         % Evaluate actual function
eps    = (-1).^[0:order+1];                 % Epsilon for coefficients calculation
p_track = [];                               % For tracking result with error
%=====

%=====
% Estimate with Polyfit and get data
%=====
% % % % pp      = polyfit(x_pts,y_act,order);% get polyfit coefficients
% % % % y_pfit  = polyval(pp,x_pts);        % evaluate with polyfit
coefficients
% % % % errPfit = y_pfit - y_act;            % get polyfit error values to
compare

%=====
% Repeat Powers of the polynomial in
% in (order +2) rows and get the
```

```

% initial x points %
%=====
set = ones(order+2,1)*([0:order+1]);
xi = (a+b)/2 + (b-a)/2*cos((set*pi)/(order+1));

% Entering conditions for the loop. First loop is the chebyshev polynomial
j = 1;
max_loops = 10; % Max loops for Remez function
% % % % ratio_error = 2;
%=====
% Remez loop, however first set of coefficients are chebyshev coefficients%
% Exit on these conditions: 1) Convergence 2) Greater than 9 iterations %
% 3) If we have an exact quadratic to approx.. %
%=====
%% while (ratio_error > 1.00000001 || ratio_error < 0.9999999) && j<max_loops
while j<max_loops
    % Extract set of initial points for evaluation (we'll use 4th column)
    % Next, evaluate the points on the actual function
    N_p = [xi(1,1); xi(1,2); xi(1,3); xi(1,4)];
    F = fun(N_p);

    % Raise x0, x1, x2, x3, to the respective powers
    A = (xi').^(set);
    A(:,4) = eps';

    %=====
    % Find Polynomial Coefficients %
    %=====
    p = A\F; % 1st time = chebyshev coefficients
    p_track = [p_track,p]; % Records error

    %=====
    % Remove err term; flip coefficients %
    %=====
    pflip = fliplr(p(1:end-1)');
    poly_coeff = pflip;

    %=====
    % Calculate Plot Values %
    %=====
    y_aprx = polyval(pflip,x_pts); % evaluate with poly coefficients

    %=====
    % Calculate the Errors, break loop if %
    % 1. function is already a Quadratic %
    % 2. If convergence has been reached %
    %=====
    errRemz = y_aprx - y_act;
    max_Err = max (errRemz(2:end-1)); % Max error (exclude ends)
    min_Err = min (errRemz(2:end-1)); % Min error (exclude ends)
    if abs(max_Err)>abs(min_Err) % Set the return value of error
        snd_Err = abs(max_Err);
    else
        snd_Err = abs(min_Err);
    end
end

```

```

% (3) Exit loop if function == quadratic (very very small error)
if abs(max_Err) < 2^-40 && abs(min_Err) < 2^-40
    oscil = 0;
% % % % %      plot_cheby(x_pts,y_apprx,y_act,y_pfit,errRemz,errPfit);
    break;      % if exact polynomial is found!!!
end

% (1) Exit loop on convergence (previous error equal to present)
if j>4
    compl=p_track(4,j);
    comp2=p_track(4,j-1);
    if compl == comp2
% %      plot_cheby(x_pts,y_apprx,y_act,y_pfit,errRemz,errPfit);
        break;
    end % if compl == comp2
end % if j>1

%=====
% Finding zeroes (Max & Min of error) %
%=====
err_der = diff(errRemz);      % Find difference between adjacent
err_sign = sign(err_der);     % points and determine the signs.
err_sign = diff(err_sign);    % Find difference between signs
errZer1 = find(err_sign == -2); % Yields either 2 or -2 where the
errZer2 = find(err_sign == 2); % original function changed sign
errZeros = [errZer1,errZer2]; % Matrix of where sign changed

%=====
% Exit Remez if too many Oscillations %
% Provide Chebyshev Coefficients. %
%=====
oscil = length (errZeros);
if oscil>order
    fprintf(' ' )
% %      warning('Too many oscillations; Chebyshev Coefficients provided.')
% %      break;
end

%=====
% Use max errors and replace x values %
%=====
new_x2 = find(errRemz == max_Err); % Index of max error point
new_x3 = find(errRemz == min_Err); % Index of min error point
% Make sure to replace into the correct order on the range
new_x2 = new_x2(1);               % Incase there are multiiple
new_x3 = new_x3(1);               % pick the first element
if new_x2 > new_x3
    xi(:,2) = a+new_x2/N*(b-a);
    xi(:,3) = a+new_x3/N*(b-a);
elseif new_x2 < new_x3
    xi(:,2) = a+new_x3/N*(b-a);
    xi(:,3) = a+new_x2/N*(b-a);
end % end if new_x2 > new_x3 statement

```



```

% % % % % % %      ratio_error = abs(max_Err)/abs(min_Err);
% % % % % % %      ratio_err_track = [ratio_err_track,ratio_error];

%=====
% Plot actual vs the approx functions %
%=====
% %      if mod(j,3)==1 || j==max_loops
% %          plot_cheby(x_pts,y_apprx,y_act,y_pfit,errRemz,errPfit);
% %          figure
% %          plot(x_pts,errFuncP)
% %      end % end if mod(j,3)==1 || j==max_loops statement
% % % %      trackj = [trackj, j];
% %      j=j+1;
end %while loop

% % % format long;
% % % ratio_err_track
% % % p_track
% % % trackj
% % % format short;

```

A.2.1 Variable Length Approximation Speed-Up Algorithms

The following files are the programs used to speed up the segmentation. 6 are presented here. The first file is the file that is used for segmentation. The others are available for the purpose of comparison. Only the first file is complete, the other files only show the code that is different from the first one i.e. the middle of the file that searches out the width for segmentation.

a. *Hybrid of 3 estimates, average and thirds*

FILE: varQuadApproxHyb3AvgThird.m

```
function [endpt,i,p,data_] = ...
    varQuadApproxHyb3AvgThird(x_pts,f3der,est_max_len,fct,epsilon,indx)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% varQuadApproxHyb3AvgThird.m
%
% This function creates a 2nd Order polynomial approximation of a given
% function using the Remez algorithm. It continues to calculate Remez
% approximations until epsilon is exceeded.
%
% Remez approximations (with first approximation being a chebychev
% polynomial approximation).
%
% To reduce the loop time, we first approximate the length of the
% proposed segment. We take 3 estimates, at the beginning, end and
% middle. Take the average of these 3. Then evaluate all the points
% on the proposed length and get set of estimated lengths.
% Take the average of all these estimates. This is the proposed length
% to be used.
%
% INPUT:
%     fct: function entered by user (want to approximate this)
%           However this function cannot be a constant. f must
%           be only one variable. Must use the variable 'x'.
%     x_pts: All the x-axis points on which to evaluate the
%            function.
%     indx: index at which to start the interval of x values
%     epsilon: maximum error that the user wants to limit the
%              approximated function.
%
% OUTPUT:
%     endpt: end point of the segment
%     i: Index at which we stopped the function approximated
%     p: coefficient for polynomial approximation
%         p(1) is the x^2 coeff, p(2) is the x coeff and
%         p(3) is the constant term in the 2nd order poly
%
% Modified by Njuguna Macaria
```

```

% Modified:      FEB  2, 2007                      Last Modified: APR 1, 2007  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
syms x
order           = 2;                               % Set the order of the polynomial
errStop         = 0;                               % To to see if we exceeded epsilon
loopt           = 1;                               % track times Remez is called
data_           = [];                             % Final loop count accumulated
x_ptsRange      = x_pts(end)-x_pts(1);             % Basically (b-a)
start_interval  = x_pts(indx);                     % Start of this segment interval

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%      ESITMATION      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%      Using Average after 3 Est      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

abs_f3der = abs(f3der(start_interval));
if abs_f3der == 0
    len = round(.086*length(x_pts)); % Close, but ends up being increased
else
    x_range1 = 4*(epsilon*3/abs_f3der)^(1/3);
    len1 = round(x_range1/(x_ptsRange)*length(x_pts));
    if len1+indx > length(x_pts)
        len = length(x_pts) - indx;
    else
        abs_f3der= abs(f3der(x_pts(indx+len1)));
        if abs_f3der == 0
            len = round(.086*length(x_pts));
        else
            x_range2 = 4*(epsilon*3/abs_f3der)^(1/3);
            len2 = round(x_range2/(x_ptsRange)*length(x_pts));
            len_mid = round((len1+len2)/4);
            abs_f3der= abs(f3der(x_pts(indx+len_mid)));
            if abs_f3der == 0
                len = round(.086*length(x_pts));
            else
                x_range3 = 4*(epsilon*3/abs_f3der)^(1/3);
                len3 = round(x_range3/(x_ptsRange)*length(x_pts));
                len = round((len1+len2+len3)/3);
            end
        end
    end
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
    end
    Der3Intr = f3der(x_pts(indx:indx+len)); % Get third derivatives
    AV3DER = mean(Der3Intr); % Average them all
    x_range = 4*(epsilon*3/abs(AV3DER))^(1/3); % Get new X_range value
    len = round(x_range/(x_ptsRange)*length(x_pts)); % Best len
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
    elseif len > est_max_len*10 % When 3rd Derivative is small
        len = est_max_len;
    end
end
end
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% LOCATE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
interval      = [start_interval,x_pts(len+indx)];
[p,oscil,errP] = chebyRemz(fct,interval,order);
max_Perr      = errP;

LOOK          = max_Perr/epsilon;

if abs_f3der == 0 || LOOK < 0.9 || LOOK > 1.002
    %=====
    % Find a good place to start indexing %
    %=====
    if abs_f3der == 0
        while (max_Perr > epsilon) && len > 2
            len = ceil(len/3);
            if len+indx > length(x_pts)
                len = length(x_pts) - indx;
                break;
            end
            interval = [start_interval,x_pts(indx+len)];
            [p,oscil,errP] = chebyRemz(fct,interval,order);
            max_Perr = errP;
            loopt = loopt + 1;
        end % while max_Perr > epsilon
        incrementLen = len;
    else
        incrementLen = ceil(len*.05);
    end % if abs_f3der == 0

    while incrementLen > 2
        incrementLen = ceil(incrementLen/3);
        while (max_Perr < epsilon) && len > 2
            len = len + incrementLen;
            if len+indx > length(x_pts)
                len = length(x_pts) - indx;
                break;
            end
            interval = [start_interval,x_pts(indx+len)];
            [p,oscil,errP] = chebyRemz(fct,interval,order);
            max_Perr = errP;
            loopt = loopt + 1;
        end % while max_Perr > epsilon

        incrementLen = ceil(incrementLen/3);

        while (max_Perr > epsilon) && len > 2
            len = len - incrementLen;
            interval = [start_interval,x_pts(indx+len)];
            [p,oscil,errP] = chebyRemz(fct,interval,order);
            max_Perr = errP;
            loopt = loopt + 1;
            if incrementLen < 2
                break;
            end
        end
    end
end

```

```

        end % max_Perr > epsilon
    end % end while incrementLen > 2
end % if

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%=====
% Step from indx + len %
%=====
if max_Perr > epsilon % Since we exceeded, go backwards
    i = indx+len; % Jump to the estimated length
    errStop = 2*epsilon; % Increase to prevent premature stop
    while i < length(x_pts)
        if errStop < epsilon
            i = i+1; % This was the point evaluated before
            endpt = x_pts(i); % the decrement at the end of this
            % while loop. Restore index i and all
            % associated data.

            fid = fopen('CompareLoop.txt','a');
            data_ = [data_ loopt];

            Der3Intr = f3der(x_pts(indx:indx+len));
            AV3DER = mean(Der3Intr);

            fprintf(fid,'\n%4d %4d len: %5d i: %5d ',...
                'avg:%10.5f LOOK: %8.6f MORE',...
                i,loopt, len, i-indx, AV3DER, LOOK);
            fclose (fid);
            return
        end
        loopt = loopt + 1;
        interval = [start_interval, x_pts(i)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        errStop = errP;
        i = i -1;
    end
else
    for i=indx+len:length(x_pts) % Since we were short, go forward
        % First time thru, skip this if statement
        % If exceeded the max error, then go back to the previous endpoint
        if errStop > epsilon
            i = i-2; % Get back to within Error
            endpt = x_pts(i);
            interval = [start_interval, x_pts(i)];
            [p,oscil,errP] = chebyRemz(fct,interval,order);
            fid = fopen('CompareLoop.txt','a');
            data_ = [data_ loopt];

            Der3Intr = f3der(x_pts(indx:indx+len));
            AV3DER = mean(Der3Intr);

            fprintf(fid,'\n%4d %4d len: %5d i: %5d ',...
                'avg:%10.5f LOOK: %8.6f LESS',...
                i,loopt, len, i-indx, AV3DER, LOOK);

```

```

        fclose (fid);
        return
    end % if error > max
    loopt      = loopt + 1;
    interval    = [start_interval, x_pts(i)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    errStop     = errP*1.05;          % reduces the iterations
end
end % max_Perr > epsilon..... % for i=indx+1:length(fct)

fid  = fopen('CompareLoop.txt','a');
data_ = [data_ loopt];
fprintf(fid,'\n%4d    %4d',i, loopt);
fclose (fid);
endpt = x_pts(i);
% END OF FILE: varQuadApproxHyb3AvgThird.m

```

b. Binary Search

FILE: varQuadApproxBinSearch.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%      BIN SEARCH      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

while (max_Perr > epsilon) && len > 2
    len          = round (len/2);
    interval     = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr     = errP;
    loopt       = loopt +1;
end % while max_Perr > epsilon

incrementLen = len;

while incrementLen > 2
    incrementLen = round(incrementLen/2);
    while (max_Perr < epsilon) && len > 1
        len          = len + incrementLen;
        if len+indx > length(x_pts)
            len = length(x_pts) - indx;
            break;
        end
        interval     = [start_interval,x_pts(indx+len)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        max_Perr     = errP;
        loopt       = loopt +1;
    end % while max_Perr > epsilon

    incrementLen = round(incrementLen/2);

    while (max_Perr > epsilon) && len > 1
        len          = len - incrementLen;
        interval     = [start_interval,x_pts(indx+len)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        max_Perr     = errP;
        loopt       = loopt +1;
        if incrementLen == 1
            break;
        end
    end % max_Perr > epsilon
end % end while incrementLen > 2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%      PINPOINT      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

c. *Thirds*

FILE: varQuadApproxTHIRD.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% THIRDS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while (max_Perr > epsilon) && len > 2
    len = round (len/3);
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
        break;
    end
    interval = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr = errP;
    loopt = loopt +1;
end % while max_Perr > epsilon

incrementLen = len;

while incrementLen > 2
    incrementLen = round(incrementLen/3);
    while (max_Perr < epsilon) && len > 2
        len = len + incrementLen;
        if len+indx > length(x_pts)
            len = length(x_pts) - indx;
            break;
        end
        interval = [start_interval,x_pts(indx+len)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        max_Perr = errP;
        loopt = loopt +1;
    end % while max_Perr > epsilon

    incrementLen = round(incrementLen/3);

    while (max_Perr > epsilon) && len > 2
        len = len - incrementLen;
        interval = [start_interval,x_pts(indx+len)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        max_Perr = errP;
        loopt = loopt +1;
        if incrementLen < 3
            break;
        end
    end % max_Perr > epsilon
end % end while incrementLen > 2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```


d. Ratios

FILE: varQuadApproxRatio.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% RATIOS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
len                = length(x_pts)-indx;

max_Perr = 100;
LOOK      = 0;
%=====
% Find a good place to start indexing %
%=====
while (max_Perr > epsilon) && len > 2
    len                = floor(len/3);
    interval           = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr          = errP;
    loopt             = loopt +1;
end

while (max_Perr < epsilon) && len > 2
    len                = ceil (len*1.2);
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
        break;
    end
    interval           = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr          = errP;
    loopt             = loopt +1;
end % max_Perr > epsilon

while (max_Perr > epsilon) && len > 2
    len                = floor(len*.95);
    interval           = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr          = errP;
    loopt             = loopt +1;
end % max_Perr > epsilon

while (max_Perr < epsilon) && len > 2
    len                = ceil (len*1.01);
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
        break;
    end
    interval           = [start_interval,x_pts(indx+len)];
    [p,oscil,errP] = chebyRemz(fct,interval,order);
    max_Perr          = errP;
    loopt             = loopt +1;
end % while max_Perr > epsilon

while (max_Perr > epsilon) && len > 2
    len                = floor (len*.999);

```

```

        if len+indx > length(x_pts)
            len = length(x_pts) - indx;
            break;
        end
        interval = [start_interval,x_pts(indx+len)];
        [p,oscil,errP] = chebyRemz(fct,interval,order);
        max_Perr = errP;
        loopt = loopt +1;
    end % while max_Perr > epsilon
% end % if

interval = [start_interval,x_pts(len+indx)];
[p,oscil,errP] = chebyRemz(fct,interval,order);
max_Perr = errP;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

e. 1 estimate

FILE: varQuadApprox1.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% ESITIMATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Using 1 Est %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

abs_f3der = abs(f3der(start_interval));
if abs_f3der == 0
    len = round(.086*length(x_pts)); % Close, but ends up being increased
else
    x_rangel = 4*(epsilon*3/abs_f3der)^(1/3);
    len = round(x_rangel/(x_ptsRange)*length(x_pts));
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
    end
end

interval = [start_interval,x_pts(len+indx)];
[p,oscil,errP] = chebyRemz(fct,interval,order);
max_Perr = errP;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

f. 2 estimates

FILE: varQuadApprox2.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% ESITMATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%.. Using 2 Est %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

abs_f3der = abs(f3der(start_interval));
if abs_f3der == 0
    len = round(.086*length(x_pts)); % Close, but ends up being increased
else
    x_rangel = 4*(epsilon*3/abs_f3der)^(1/3);
    len1 = round(x_rangel/(x_ptsRange)*length(x_pts));
    if len1+indx > length(x_pts)
        len = length(x_pts) - indx;
    else
        abs_f3der= abs(f3der(x_pts(indx+len1)));
        if abs_f3der == 0
            len = est_max_len;
        else
            x_range2 = 4*(epsilon*3/abs_f3der)^(1/3);
            len2 = round(x_range2/(x_ptsRange)*length(x_pts));
            len = round((len1+len2)/2);
        end
    end
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
    end
end

interval = [start_interval,x_pts(len+indx)];
[p,oscil,errP] = chebyRemz(fct,interval,order);
max_Perr = errP;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

g. 3 estimates

FILE: varQuadApprox3.m

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% ESITMATION %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Using 3 Est %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

abs_f3der = abs(f3der(start_interval));
if abs_f3der == 0
    len = round(.086*length(x_pts)); % Close, but ends up being increased
else
    x_range1 = 4*(epsilon*3/abs_f3der)^(1/3);
    len1 = round(x_range1/(x_ptsRange)*length(x_pts));
    if len1+indx > length(x_pts)
        len = length(x_pts) - indx;
    else
        abs_f3der= abs(f3der(x_pts(indx+len1)));
        if abs_f3der == 0
            len = est_max_len;
        else
            x_range2 = 4*(epsilon*3/abs_f3der)^(1/3);
            len2 = round(x_range2/(x_ptsRange)*length(x_pts));
            len_mid = round((len1+len2)/4);
            abs_f3der= abs(f3der(x_pts(indx+len_mid)));
            if abs_f3der == 0
                len = est_max_len;
            else
                x_range3 = 4*(epsilon*3/abs_f3der)^(1/3);
                len3 = round(x_range3/(x_ptsRange)*length(x_pts));
                len = round((len1+len2+len3)/3);
            end
        end
    end
    if len+indx > length(x_pts)
        len = length(x_pts) - indx;
    elseif len > est_max_len*10 % When 3rd Derivative is small
        len = est_max_len;
    end
end
end

interval = [start_interval,x_pts(len+indx)];
[p,oscil,errP] = chebyRemz(fct,interval,order);
max_Perr = errP;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% PINPOINT %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

A.2.2 Non-Uniform Quadratic Approximation

This is the file that keeps track of the segments computed and the associated endpoints and coefficients. The data is sent back to the main function, QuadAppxRemz.m. From we call *varQuadApproxHyb3AvgThird.m* or any of the other *varQuadApprox** files depending on which one we want to use.

FILE: multipleQuadApprox.m

```
function [endpt,indx,c2,c1,c0] = multipleQuadApprox(xpts,fct,epsilon)

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function will produce multiple Quadratic-line approximations of a %
% given function to within the bounds of max error provided. %
% Created: January, 2007 %
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% INPUT: %
%         fct: function entered by user (want to approximate this) %
%         However this function cannot be a constant. f must %
%         be only one variable. Must use the variable 'x'. %
%         xpts: All the x-axis points on which to evaluate the %
%         function. %
%         epsilon: maximum error that the user wants to limit the %
%         approximated function. %
%
% OUTPUT: %
%         endpt: end point of the segment %
%         indx: Array of all the index endpoints %
%         c2: Array of the x^2 polynomial coefficients %
%         c1: Array of the x polynomial coefficients %
%         c0: Array of the constant terms in the 2nd order poly %
%
% Modified: July 2, 2007 %
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

syms x
format compact
i      = 1;
seg_no = 1;
endpt  = [];
c2     = [];
c1     = [];
c0     = [];

%=====
% Find Max length Estimate. Will be %
% used if third derivative = 0, or if %
% it's really small (NOT YET IMPEMETED) %
%=====
fct_vec      = inline(vectorize(fct));
abs_f3der    = abs(diff(diff(diff(fct))));
abs_f3der_vec= inline(vectorize(abs_f3der));
```

```

f3der_pts    = abs(abs_f3der_vec(xpts));
abs_f3der_max= max(f3der_pts);           % Absolute Max 3rd derivative
x_ptsRange   = xpts(end)-xpts(1);

xpts_min_seg = 4*(epsilon*3/abs_f3der_max)^(1/3); % smallest seg width
min_seg_len   = round(xpts_min_seg/x_ptsRange*length(xpts));
xpts_avg_seg  = 4*(epsilon*3*x_ptsRange/...
    quadl(abs_f3der_vec,xpts(1),xpts(end)))^(1/3);
avg_seg_len   = round(xpts_avg_seg/x_ptsRange*length(xpts));
est_max_len   = 2*avg_seg_len - min_seg_len;

% If the function is sqrt(-log(x)), then make est_max_len the max size.
% est_max_len calculated is not as large as the larger segments and will
% slow down the program because of small estimates...Therefore:
if fct == sqrt(-log(x))
    est_max_len = length(xpts);
end

% Sometimes the estimates are short. To prevent this from affecting the
% program... est_max_len is increased * 10
% est_max_len = 10*est_max_len;

%=====
% Get the values for each segment and %
% store them in the return vectors %
%=====
indx(i)= 1; % To include the first element, offset length by 1
while i < length(xpts)
    [endpt(seg_no),indx(seg_no+1),polyCoeff] = ...
        varQuadApproxHyb3AvgThird (xpts,abs_f3der_vec,...
            est_max_len,fct_vec,epsilon,i);

    c2(seg_no) = polyCoeff(1);
    c1(seg_no) = polyCoeff(2);
    c0(seg_no) = polyCoeff(3);
    i          = indx(seg_no+1);
    seg_no     = seg_no + 1;
end
fprintf('\n\n*****End of Segmentation*****\n\n');
avg_seg_len
min_seg_len
est_max_len
Seg_lengths = diff(indx)

```

A.2.3 Uniform Quadratic Approximation

FILE: constantQuadApprox.m

```
function [endpt,indx,c2,c1,c0] = constantQuadApprox(x_pts,fct,constsegs)
%
% This function produces multiple Quadratic approximations of a
% given function to within the bounds of the number of segments provided.
% Coefficients calculated by Remez.
%
% Created by Tom Mack for linear approximations, using polyfit
% Created: June 4, 2006
% Modified for Quadratic approximations using Remez by Njuguna Macaria
% Modified: July 11, 2006
%

syms x
order = 2;
indx(1) = 1;

for i = 1:constsegs
    indx(i+1) = round((length(x_pts)/constsegs)*i); % each iteration set seg
size
    if i==constsegs
        indx(i+1) = length(x_pts);
    end
    endpt(i) = x_pts(indx(i+1));
    interval = [x_pts(indx(i)),endpt(i)];
    [p,oscl,errP] = chebyRemz(fct,interval,order);
    c2(i) = p(1);
    c1(i) = p(2);
    c0(i) = p(3);
    i = i+1;
end
```

A.2.4 Uniform Quadratic Approximation with Constraints

FILE: constQuadAppxWErr.m

```
function [endpt,indx,c2,c1,c0] = constQuadAppxWErr(xpts,fct,epsilon)

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function will produce multiple Quadratic-line approximations of a %
% constant size of a given function to within the bounds of the max error %
% provided. Coefficients & intercept calculated using Chebychev and %
% algorithm. %
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% INPUT: %
%         fct: function entered by user (want to approximate this) %
%         However this function cannot be a constant. f must %
%         be only one variable. Must use the variable 'x'. %
%         x_pts: All the x-axis points on which to evaluate the %
%         function. %
%         indx: index at which to start the interval of x values %
%         epsilon: maximum error that the user wants to limit the %
%         approximated function. %
% OUTPUT: %
%         endpt: end point of the segment %
%         c2: Coefficients of x^2 in quadratic polynomial %
%         c1: Coefficients of x in quadratic polynomial %
%         c0: Constant of quadratic polynomial %
% Compute # of seg %
% Author: Njuguna Macaria %
% Date: 5 July 2007 %
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

syms x

%=====
% Find Min length Estimate. Will be %
% the limiting length for uniform %
% implmentation %
%=====
fct_vec = inline(vectorize(fct)); % vectorize fct (for eval)
abs_f3der = abs(diff(diff(diff(fct)))); % symbolic 3rd derivative
abs_f3der_vec = inline(vectorize(abs_f3der)); % vectorize for evaluation
f3der_pts = abs(abs_f3der_vec(xpts)); % evaluate to form vector
abs_f3der_max = max(f3der_pts); % abs (Max 3rd derivative)
x_ptsRange = xpts(end)-xpts(1); % Find length of x-domain

xpts_min_seg = 4*(epsilon*3/abs_f3der_max)^(1/3); % smallest domain len
est_min_seglen = floor(xpts_min_seg/x_ptsRange*length(xpts)) %in index pts

%=====
% Find where this happens in the domain %
%=====
IndxofMax = find(f3der_pts == abs_f3der_max); % Find min len on domain
numoftimes = length(IndxofMax); % How many are there?

%=====
% Test begin, End and Midddle %
%=====
```



```

est_max_len = length(xpts); % dummy variable
if numoftimes > 1 % more than 1 Max point
    i = IndxofMax(1); % i at begin of est seg
else
    i = IndxofMax; % default
end
IndMaxtmp = i; % The new IndexofMax

if i > length(xpts) - est_min_seglen % Check if truncated
    lenBegin = est_min_seglen; % segment then fix
    lenMid = est_min_seglen; % both these estimates
else
    % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
    % Begin with the index of the highest 3rd derivative
    [endpt,indx,p] = varQuadApproxHyb3AvgThird( xpts,...
                                                abs_f3der_vec, ...
                                                est_max_len, ...
                                                fct_vec, ...
                                                epsilon,...
                                                i);

    lenBegin = indx - i;

    % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
    % index of the highest 3rd derivative in the middle
    i = IndMaxtmp - floor(est_min_seglen/2); % is at end of est seg
    if i < 1 % Check to make sure not indexing before begin
        i = 1; % of interval, if so start at begin of interval
    end
    [endpt,indx,p] = varQuadApproxHyb3AvgThird( xpts,...
                                                abs_f3der_vec, ...
                                                est_max_len, ...
                                                fct_vec, ...
                                                epsilon,...
                                                i);

    lenMid = indx - i;

end

% % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% end with the index of the highest 3rd derivative
i = IndMaxtmp - est_min_seglen; % is at end of est seg
if i < 1 % Check to make sure not indexing before begin
    i = 1; % of interval, if so start at begin of interval
end
[endpt,indx,p] = varQuadApproxHyb3AvgThird( xpts,...
                                                abs_f3der_vec, ...
                                                est_max_len, ...
                                                fct_vec, ...
                                                epsilon,...
                                                i);

lenEnd = indx - i;

%=====

```

```

% Find # of required segments on domain %
%=====
min_seglen    = min([lenBegin,lenMid,lenEnd,est_min_seglen]);
numberOfSegs  = ceil(length(xpts)/(min_seglen-1)); % Go large, figure # segs

%=====
% Reuse the function to calculate data %
%=====
[endpt,indx,c2,c1,c0] = constantQuadApprox(xpts,fct_vec,numberOfSegs);

```

A.2.5 Fixed-Point Decimal to HEXADECIMAL or BINARY

FILE: twosComp.m

```
%function [hexX,decX,binX] = twosComp(x,intLen,mantisaLen)
function hexX = twosComp(x,intLen,mantisaLen)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% twosComp.m
%
% This function converts any decimal number to a two's complement binary
% fi object.
%
% function [hex, decX, binX] = twosComp(x,intLen,mantisaLen)
%
% Input:          x:      The value to be converted
%                intLen:  User desired length of the integer portion of
%                        the number. How many bits are in the integer.
%                mantisaLen: The length of the mantissa. The number of bits
%                        in the fraction section, the precision.
% Output:         decX:   Decimal value as fi object. Integer and
%                        fraction as decimal representation.
%                binX:   Two's Complement of the input x. With integer
%                        portion represented with "intLen" bits and the
%                        fraction portion represented with "mantisaLen"
%                        bits.
%                hexX:   Two's Complement of the input x. Represented
%                        as a Hexadecimal value.
%
% This function auto-aligns the decimal point.
%
% Created by:  Njuguna Macaria
% Date:  10 May 2007
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

totalLen = intLen+mantisaLen; % Total bits desired to represent the nbr.
if totalLen >128
    warning('Max Precision: 128bits. You have requested > 128 bits');
end

% ===== %
% fi Object: two's complement %
% ===== %
decX = fi(x,1,totalLen,mantisaLen); % Create fi object, display decimal
binX = bin(decX); % Save and return a binary form
hexX = hex(decX);
deciM = dec(decX);

% ===== %
% Quantizer: two's complement %
% ===== %
% % q = quantizer('fixed', 'nearest', 'saturate',[totalLen mantisaLen])
% % [a,b] = range(q)
% % binX = num2bin(q,x)
% % decX = bin2num(q,b)
```

A.2.6 User Interface and Function Information Files

FILE: UserInput.m

```
function select = UserInput()

format long g
fprintf('\n\n' )
fprintf('*****')
fprintf('\n\n' )
fprintf('\n      QUADRATIC APPROXIMATION OF A FUNCTION USING CHEBYSHEV')
fprintf('\n                        AND REMEZ ALGORITHM' )
fprintf('\n' )
fprintf('\n' )

disp('*****')
disp('Functions to be compared          Interval' )
disp(' 1.  2^x          [0,1]' )
disp(' 2.  1/x          [1,2]' )
disp(' 3.  sqrt(x)       [1,2]' )
disp(' 4.  1/sqrt(x)     [1,2]' )
disp(' 5.  log2(x)       [1,2]' )
disp(' 6.  log(x)  = ln(x) [1,2]' )
disp(' 7.  sin(pi*x)     [0,1/2]' )
disp(' 8.  cos(pi*x)     [0,1/2]' )
disp(' 9.  tan(pi*x)     [0,1/4]' )
disp(' 10. sqrt(-log(x)) = sqrt(-ln(x)) [1/512,1/4]' )
disp(' 11. tan(pi*x)^2 + 1 [0,1/4]' )
disp(' 12. -(x*log2(x) + (1-x)*log2(1-x)) [1/256,1-1/256]' )
disp(' 13. 1/(1+exp(-x)) = 1/(1+e^(-x)) [0,1]' )
disp(' 14. (1/sqrt(2*pi))*exp(-x^2/2) [0,sqrt(2)]' )
disp(' 15. sin(exp(x))   [0,2]' )
disp('*****')

% Get FUNCTION to be approximated (user input)
select = input( 'Input the Function, func[sqrt(-1*log(x))]: ');
if isempty(select)
    select = 10; % default
end
```

FILE: getF.m

```
function [func,interval,vari_or_const,err_or_segs,consegs,epsilon,N]=...
                                                getF(fnc_choice);

syms x
interval    = '[1/256, 1/4]';           %% default
err_or_segs = 0;                       %% default
consegs     = 200;                     %% default
epsilon     = 0.0001;                 %% default

switch fnc_choice
    case 1
        func      = '2^x';
        interval  = '[0,1]';
    case 2
        func      = '1./x';
        interval  = '[1,2]';
    case 3
        func      = 'sqrt(x)';
        interval  = '[1,2]';
    case 4
        func      = '1/sqrt(x)';
        interval  = '[1,2]';
    case 5
        func      = 'log2(x)';
        interval  = '[1,2]';
    case 6
        func      = 'log(x)';
        interval  = '[1,2]';
    case 7
        func      = 'sin(pi*x)';
        interval  = '[0,1/2]';
    case 8
        func      = 'cos(pi*x)';
        interval  = '[0,1/2]';
    case 9
        func      = 'tan(pi*x)';
        interval  = '[0,1/4]';
    case 10
        func      = 'sqrt(-log(x))';
        interval  = '[1/512,1/4]';
    case 11
        func      = 'tan(pi*x).^2 + 1';
        interval  = '[0,1/4]';
    case 12
        func      = '-(x*log2(x) + (1-x)*log2(1-x))';
        interval  = '[1/256,1-1/256]';
    case 13
        func      = '1/(1+exp(-x))';
        interval  = '[0,1]';
    case 14
        func      = '(1/sqrt(2*pi))*exp(-x^2/2)';
        interval  = '[0,sqrt(2)]';
    case 15
        func      = 'sin(exp(x))';
```

```

        interval = '[0,2]';
end %switch fnc_choice

% Get CONSTANT OF VARIABLE segmentation (User input)
vari_or_const = 0;
while vari_or_const ~= 1 && vari_or_const ~= 2 && vari_or_const ~= 3
    vari_or_const = input( '(1)Non-uniform (2)Uniform Segmentation [1]: ');
    if isempty(vari_or_const)
        vari_or_const = 1;           %% default Non-uniform
    end
end

% If non-uniform segmentation, then enter ERROR parameters
if vari_or_const ~= 2
    epsilon = input( 'Input the Desired Error, epsilon[2^-33]: ');
    if isempty(epsilon)
        epsilon = 2^-33;           %% default
    end
end

% If uniform segmentation, find how the user will restrict # of segments
if vari_or_const == 2
    err_or_segs = input( 'Constrain by (1)Number of Segments or (2)Error [1:]');
    if isempty(err_or_segs)
        err_or_segs = 1;           %% default
    end
    if err_or_segs == 1
        consegs = input( 'Input the number of Desired Segments[20]: ');
        if isempty(consegs)
            consegs = 20;           %% default
        end
    end
    if err_or_segs == 2
        epsilon = input( 'Input the given_error; epsilon[2^-16]: ');
        if isempty(epsilon)
            epsilon = 2^-16;           %% default
        end
    end
end

N = input( 'Input the no. of pts the fct is to be evaluated, N[1000000]: ');
if isempty(N)
    N = 1000000;                   %% default
end

```

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APPENDIX B. HDL CODE

B.1 MULTIPLIER CODE

The VHDL code was adapted from Xilinx's application note on pipelining a multiplier in the Virtex II family of chips[22]. The code is for 32 bit inputs and one 32 bit product with the decimal point in the middle; 16 bit integer and 16 bit fraction.

1. VHDL

```
-----
-- School:          NPS - Naval Postgraduate School, Monterey
-- Student:         Njuguna Macaria
--
-- Create Date:     14:10:56 07/07/07
-- Design Name:
-- Module Name:     mult_32to32 - Behavioral
-- Project Name:
-- Target Device:   xc2v6000-4ff1517 (virtex II in SRC-6)
-- Tool versions:   Xilinx 6.303i and Synplicity 8.1
-- Simulation:      Modelsim and Synplicity's simulation tool
-- Description:
--
-- Dependencies:    Modified from
--
-- Revision:
-- Revision 0.01 - File Created
-- Additional Comments:
--
-----
--***** COMPONENTS NEEDED *****
-----

-- UNSIGNED 16 BIT MULTIPLIER --
-----

library ieee;
use ieee.std_logic_1164.all;
Library UNISIM;
use UNISIM.vcomponents.all;

-- Entity: Description of pins (PORTS)
entity mult16_32 is
    port(
        au, bu: in std_logic_vector (15 downto 0);
        clk : in std_logic;
        produ : out std_logic_vector(31 downto 0));
end mult16_32;

architecture mult16_32_beh of mult16_32 is
```



```

component FDR
  port(
    Q : out   STD_ULONGIC;
    D : in    STD_ULONGIC;
    C : in    STD_ULONGIC;
    R : in    STD_ULONGIC);
end component;

component MULT18X18S
  port (A : in  STD_LOGIC_VECTOR (17 downto 0);
        B : in  STD_LOGIC_VECTOR (17 downto 0);
        C : in  STD_ULONGIC ;
        CE : in  STD_ULONGIC ;
        P : out STD_LOGIC_VECTOR (35 downto 0);
        R : in  STD_ULONGIC );
end component;

signal a_wire, b_wire: std_logic_vector(15 downto 0);
signal      p_wire: std_logic_vector(31 downto 0);
signal      discard: std_logic_vector( 3 downto 0);

attribute RLOC : string;

attribute RLOC of REG_A0 : label is "X0Y0" ;
attribute RLOC of REG_A1 : label is "X0Y0" ;
attribute RLOC of REG_A2 : label is "X0Y1" ;
attribute RLOC of REG_A3 : label is "X0Y1" ;
attribute RLOC of REG_A4 : label is "X0Y2" ;
attribute RLOC of REG_A5 : label is "X0Y2" ;
attribute RLOC of REG_A6 : label is "X0Y3" ;
attribute RLOC of REG_A7 : label is "X0Y3" ;
attribute RLOC of REG_A8 : label is "X0Y4" ;
attribute RLOC of REG_A9 : label is "X0Y4" ;
attribute RLOC of REG_A10: label is "X0Y5" ;
attribute RLOC of REG_A11: label is "X0Y5" ;
attribute RLOC of REG_A12: label is "X0Y6" ;
attribute RLOC of REG_A13: label is "X0Y6" ;
attribute RLOC of REG_A14: label is "X0Y7" ;
attribute RLOC of REG_A15: label is "X0Y7" ;
-- attribute RLOC of REG_A16: label is "X-1Y7";
-- attribute RLOC of REG_A17: label is "X-1Y7";

attribute RLOC of REG_B0 : label is "X2Y0" ;
attribute RLOC of REG_B1 : label is "X2Y0" ;
attribute RLOC of REG_B2 : label is "X2Y1" ;
attribute RLOC of REG_B3 : label is "X2Y1" ;
attribute RLOC of REG_B4 : label is "X2Y2" ;
attribute RLOC of REG_B5 : label is "X2Y2" ;
attribute RLOC of REG_B6 : label is "X2Y3" ;
attribute RLOC of REG_B7 : label is "X2Y3" ;
attribute RLOC of REG_B8 : label is "X2Y4" ;
attribute RLOC of REG_B9 : label is "X2Y4" ;
attribute RLOC of REG_B10: label is "X2Y5" ;
attribute RLOC of REG_B11: label is "X2Y5" ;
attribute RLOC of REG_B12: label is "X2Y6" ;

```

```

attribute RLOC of REG_B13: label is "X2Y6" ;
attribute RLOC of REG_B14: label is "X2Y7" ;
attribute RLOC of REG_B15: label is "X2Y7" ;
-- attribute RLOC of REG_B16: label is "X-1Y6";
-- attribute RLOC of REG_B17: label is "X-1Y6";

attribute RLOC of REG_P0 : label is "X-2Y0";
attribute RLOC of REG_P1 : label is "X1Y0" ;
attribute RLOC of REG_P2 : label is "X1Y0" ;
attribute RLOC of REG_P3 : label is "X1Y1" ;
attribute RLOC of REG_P4 : label is "X1Y1" ;
attribute RLOC of REG_P5 : label is "X3Y0" ;
attribute RLOC of REG_P6 : label is "X3Y0" ;
attribute RLOC of REG_P7 : label is "X3Y1" ;
attribute RLOC of REG_P8 : label is "X-2Y2";
attribute RLOC of REG_P9 : label is "X1Y2" ;
attribute RLOC of REG_P10: label is "X1Y2" ;
attribute RLOC of REG_P11: label is "X1Y3" ;
attribute RLOC of REG_P12: label is "X1Y3" ;
attribute RLOC of REG_P13: label is "X3Y2" ;
attribute RLOC of REG_P14: label is "X3Y2" ;
attribute RLOC of REG_P15: label is "X3Y3" ;
attribute RLOC of REG_P16: label is "X-2Y4";
attribute RLOC of REG_P17: label is "X1Y4" ;
attribute RLOC of REG_P18: label is "X1Y4" ;
attribute RLOC of REG_P19: label is "X1Y5" ;
attribute RLOC of REG_P20: label is "X1Y5" ;
attribute RLOC of REG_P21: label is "X3Y4" ;
attribute RLOC of REG_P22: label is "X3Y4" ;
attribute RLOC of REG_P23: label is "X3Y5" ;
attribute RLOC of REG_P24: label is "X-2Y6";
attribute RLOC of REG_P25: label is "X1Y6" ;
attribute RLOC of REG_P26: label is "X1Y6" ;
attribute RLOC of REG_P27: label is "X1Y7" ;
attribute RLOC of REG_P28: label is "X1Y7" ;
attribute RLOC of REG_P29: label is "X3Y6" ;
attribute RLOC of REG_P30: label is "X3Y6" ;
attribute RLOC of REG_P31: label is "X3Y7" ;
-- attribute RLOC of REG_P32: label is "X3Y1" ;
-- attribute RLOC of REG_P33: label is "X3Y3" ;
-- attribute RLOC of REG_P34: label is "X3Y5" ;
-- attribute RLOC of REG_P35: label is "X3Y7" ;

attribute BEL : string;

attribute BEL of REG_A0 : label is "FFX" ;
attribute BEL of REG_A1 : label is "FFY" ;
attribute BEL of REG_A2 : label is "FFX" ;
attribute BEL of REG_A3 : label is "FFY" ;
attribute BEL of REG_A4 : label is "FFX" ;
attribute BEL of REG_A5 : label is "FFY" ;
attribute BEL of REG_A6 : label is "FFX" ;
attribute BEL of REG_A7 : label is "FFY" ;
attribute BEL of REG_A8 : label is "FFX" ;
attribute BEL of REG_A9 : label is "FFY" ;

```

```

attribute BEL of REG_A10: label is "FFX" ;
attribute BEL of REG_A11: label is "FFY" ;
attribute BEL of REG_A12: label is "FFX" ;
attribute BEL of REG_A13: label is "FFY" ;
attribute BEL of REG_A14: label is "FFX" ;
attribute BEL of REG_A15: label is "FFY" ;
-- attribute BEL of REG_A16: label is "FFX" ;
-- attribute BEL of REG_A17: label is "FFY" ;

attribute BEL of REG_B0 : label is "FFX" ;
attribute BEL of REG_B1 : label is "FFY" ;
attribute BEL of REG_B2 : label is "FFX" ;
attribute BEL of REG_B3 : label is "FFY" ;
attribute BEL of REG_B4 : label is "FFX" ;
attribute BEL of REG_B5 : label is "FFY" ;
attribute BEL of REG_B6 : label is "FFX" ;
attribute BEL of REG_B7 : label is "FFY" ;
attribute BEL of REG_B8 : label is "FFX" ;
attribute BEL of REG_B9 : label is "FFY" ;
attribute BEL of REG_B10: label is "FFX" ;
attribute BEL of REG_B11: label is "FFY" ;
attribute BEL of REG_B12: label is "FFX" ;
attribute BEL of REG_B13: label is "FFY" ;
attribute BEL of REG_B14: label is "FFX" ;
attribute BEL of REG_B15: label is "FFY" ;
-- attribute BEL of REG_B16: label is "FFX" ;
-- attribute BEL of REG_B17: label is "FFY" ;

attribute BEL of REG_P0 : label is "FFY" ;
attribute BEL of REG_P1 : label is "FFX" ;
attribute BEL of REG_P2 : label is "FFY" ;
attribute BEL of REG_P3 : label is "FFX" ;
attribute BEL of REG_P4 : label is "FFY" ;
attribute BEL of REG_P5 : label is "FFX" ;
attribute BEL of REG_P6 : label is "FFY" ;
attribute BEL of REG_P7 : label is "FFX" ;
attribute BEL of REG_P8 : label is "FFY" ;
attribute BEL of REG_P9 : label is "FFX" ;
attribute BEL of REG_P10: label is "FFY" ;
attribute BEL of REG_P11: label is "FFX" ;
attribute BEL of REG_P12: label is "FFY" ;
attribute BEL of REG_P13: label is "FFX" ;
attribute BEL of REG_P14: label is "FFY" ;
attribute BEL of REG_P15: label is "FFX" ;
attribute BEL of REG_P16: label is "FFY" ;
attribute BEL of REG_P17: label is "FFX" ;
attribute BEL of REG_P18: label is "FFY" ;
attribute BEL of REG_P19: label is "FFX" ;
attribute BEL of REG_P20: label is "FFY" ;
attribute BEL of REG_P21: label is "FFX" ;
attribute BEL of REG_P22: label is "FFY" ;
attribute BEL of REG_P23: label is "FFX" ;
attribute BEL of REG_P24: label is "FFY" ;
attribute BEL of REG_P25: label is "FFX" ;
attribute BEL of REG_P26: label is "FFY" ;

```

```

attribute BEL of REG_P27: label is "FFX" ;
attribute BEL of REG_P28: label is "FFY" ;
attribute BEL of REG_P29: label is "FFX" ;
attribute BEL of REG_P30: label is "FFY" ;
attribute BEL of REG_P31: label is "FFX" ;
-- attribute BEL of REG_P32: label is "FFY" ;
-- attribute BEL of REG_P33: label is "FFY" ;
-- attribute BEL of REG_P34: label is "FFY" ;
-- attribute BEL of REG_P35: label is "FFY" ;

begin

    REG_A0  : FDR port map(Q => a_wire(0)  , C => CLK, D => au(0)  , R
=> '0');
    REG_A1  : FDR port map(Q => a_wire(1)  , C => CLK, D => au(1)  , R
=> '0');
    REG_A2  : FDR port map(Q => a_wire(2)  , C => CLK, D => au(2)  , R
=> '0');
    REG_A3  : FDR port map(Q => a_wire(3)  , C => CLK, D => au(3)  , R
=> '0');
    REG_A4  : FDR port map(Q => a_wire(4)  , C => CLK, D => au(4)  , R
=> '0');
    REG_A5  : FDR port map(Q => a_wire(5)  , C => CLK, D => au(5)  , R
=> '0');
    REG_A6  : FDR port map(Q => a_wire(6)  , C => CLK, D => au(6)  , R
=> '0');
    REG_A7  : FDR port map(Q => a_wire(7)  , C => CLK, D => au(7)  , R
=> '0');
    REG_A8  : FDR port map(Q => a_wire(8)  , C => CLK, D => au(8)  , R
=> '0');
    REG_A9  : FDR port map(Q => a_wire(9)  , C => CLK, D => au(9)  , R
=> '0');
    REG_A10 : FDR port map(Q => a_wire(10) , C => CLK, D => au(10) , R
=> '0');
    REG_A11 : FDR port map(Q => a_wire(11) , C => CLK, D => au(11) , R
=> '0');
    REG_A12 : FDR port map(Q => a_wire(12) , C => CLK, D => au(12) , R
=> '0');
    REG_A13 : FDR port map(Q => a_wire(13) , C => CLK, D => au(13) , R
=> '0');
    REG_A14 : FDR port map(Q => a_wire(14) , C => CLK, D => au(14) , R
=> '0');
    REG_A15 : FDR port map(Q => a_wire(15) , C => CLK, D => au(15) , R
=> '0');
--    REG_A16 : FDR port map(Q => a_wire(16) , C => CLK, D => '0'
, R => '0');
--    REG_A17 : FDR port map(Q => a_wire(17) , C => CLK, D => '0'
, R => '0');

    REG_B0  : FDR port map(Q => b_wire(0)  , C => CLK, D => bu(0)  , R
=> '0');
    REG_B1  : FDR port map(Q => b_wire(1)  , C => CLK, D => bu(1)  , R
=> '0');
    REG_B2  : FDR port map(Q => b_wire(2)  , C => CLK, D => bu(2)  , R
=> '0');

```

```

    REG_B3  : FDR port map(Q => b_wire(3) , C => CLK, D => bu(3) , R
=> '0');
    REG_B4  : FDR port map(Q => b_wire(4) , C => CLK, D => bu(4) , R
=> '0');
    REG_B5  : FDR port map(Q => b_wire(5) , C => CLK, D => bu(5) , R
=> '0');
    REG_B6  : FDR port map(Q => b_wire(6) , C => CLK, D => bu(6) , R
=> '0');
    REG_B7  : FDR port map(Q => b_wire(7) , C => CLK, D => bu(7) , R
=> '0');
    REG_B8  : FDR port map(Q => b_wire(8) , C => CLK, D => bu(8) , R
=> '0');
    REG_B9  : FDR port map(Q => b_wire(9) , C => CLK, D => bu(9) , R
=> '0');
    REG_B10 : FDR port map(Q => b_wire(10) , C => CLK, D => bu(10) , R
=> '0');
    REG_B11 : FDR port map(Q => b_wire(11) , C => CLK, D => bu(11) , R
=> '0');
    REG_B12 : FDR port map(Q => b_wire(12) , C => CLK, D => bu(12) , R
=> '0');
    REG_B13 : FDR port map(Q => b_wire(13) , C => CLK, D => bu(13) , R
=> '0');
    REG_B14 : FDR port map(Q => b_wire(14) , C => CLK, D => bu(14) , R
=> '0');
    REG_B15 : FDR port map(Q => b_wire(15) , C => CLK, D => bu(15) , R
=> '0');
--    REG_B16 : FDR port map(Q => b_wire(16) , C => CLK, D => '0'
, R => '0');
--    REG_B17 : FDR port map(Q => b_wire(17) , C => CLK, D => '0'
, R => '0');

    Mult1 : MULT18X18S
        port map(P(31 downto 0) => p_wire, P (35 downto 32) => discard(3
downto 0),
                A (17 downto 16) => "00", A(15 downto 0) => a_wire,
                B (17 downto 16) => "00", B(15 downto 0) => b_wire,
                C  => CLK,
                CE => '1',
                R  => '0');

    REG_P0  : FDR port map(Q => produ(0) , C => CLK, D => p_wire(0) ,
R => '0');
    REG_P1  : FDR port map(Q => produ(1) , C => CLK, D => p_wire(1) ,
R => '0');
    REG_P2  : FDR port map(Q => produ(2) , C => CLK, D => p_wire(2) ,
R => '0');
    REG_P3  : FDR port map(Q => produ(3) , C => CLK, D => p_wire(3) ,
R => '0');
    REG_P4  : FDR port map(Q => produ(4) , C => CLK, D => p_wire(4) ,
R => '0');
    REG_P5  : FDR port map(Q => produ(5) , C => CLK, D => p_wire(5) ,
R => '0');
    REG_P6  : FDR port map(Q => produ(6) , C => CLK, D => p_wire(6) ,
R => '0');
    REG_P7  : FDR port map(Q => produ(7) , C => CLK, D => p_wire(7) ,

```

```

R => '0');
  REG_P8   : FDR port map(Q => produ(8)   , C => CLK, D => p_wire(8)   ,
R => '0');
  REG_P9   : FDR port map(Q => produ(9)   , C => CLK, D => p_wire(9)   ,
R => '0');
  REG_P10  : FDR port map(Q => produ(10)  , C => CLK, D => p_wire(10)  ,
R => '0');
  REG_P11  : FDR port map(Q => produ(11)  , C => CLK, D => p_wire(11)  ,
R => '0');
  REG_P12  : FDR port map(Q => produ(12)  , C => CLK, D => p_wire(12)  ,
R => '0');
  REG_P13  : FDR port map(Q => produ(13)  , C => CLK, D => p_wire(13)  ,
R => '0');
  REG_P14  : FDR port map(Q => produ(14)  , C => CLK, D => p_wire(14)  ,
R => '0');
  REG_P15  : FDR port map(Q => produ(15)  , C => CLK, D => p_wire(15)  ,
R => '0');
  REG_P16  : FDR port map(Q => produ(16)  , C => CLK, D => p_wire(16)  ,
R => '0');
  REG_P17  : FDR port map(Q => produ(17)  , C => CLK, D => p_wire(17)  ,
R => '0');
  REG_P18  : FDR port map(Q => produ(18)  , C => CLK, D => p_wire(18)  ,
R => '0');
  REG_P19  : FDR port map(Q => produ(19)  , C => CLK, D => p_wire(19)  ,
R => '0');
  REG_P20  : FDR port map(Q => produ(20)  , C => CLK, D => p_wire(20)  ,
R => '0');
  REG_P21  : FDR port map(Q => produ(21)  , C => CLK, D => p_wire(21)  ,
R => '0');
  REG_P22  : FDR port map(Q => produ(22)  , C => CLK, D => p_wire(22)  ,
R => '0');
  REG_P23  : FDR port map(Q => produ(23)  , C => CLK, D => p_wire(23)  ,
R => '0');
  REG_P24  : FDR port map(Q => produ(24)  , C => CLK, D => p_wire(24)  ,
R => '0');
  REG_P25  : FDR port map(Q => produ(25)  , C => CLK, D => p_wire(25)  ,
R => '0');
  REG_P26  : FDR port map(Q => produ(26)  , C => CLK, D => p_wire(26)  ,
R => '0');
  REG_P27  : FDR port map(Q => produ(27)  , C => CLK, D => p_wire(27)  ,
R => '0');
  REG_P28  : FDR port map(Q => produ(28)  , C => CLK, D => p_wire(28)  ,
R => '0');
  REG_P29  : FDR port map(Q => produ(29)  , C => CLK, D => p_wire(29)  ,
R => '0');
  REG_P30  : FDR port map(Q => produ(30)  , C => CLK, D => p_wire(30)  ,
R => '0');
  REG_P31  : FDR port map(Q => produ(31)  , C => CLK, D => p_wire(31)  ,
R => '0');
--      REG_P32 : FDR port map(Q => discard( 3)   , C => CLK, D =>
p_wire(32) , R => '0');
--      REG_P33 : FDR port map(Q => discard( 2)   , C => CLK, D =>
p_wire(33) , R => '0');
--      REG_P34 : FDR port map(Q => discard( 1)   , C => CLK, D =>
p_wire(34) , R => '0');

```

```

--      REG_P35 : FDR port map(Q => discard( 0)      , C => CLK, D =>
p_wire(35) , R => '0');

end mult16_32_beh;

-----
--      32 BIT MULTIPLIER      --
-----

library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

entity mult_32to32 is
PORT (
    a, b : in std_logic_vector (31 downto 0) ;
    clk : in std_logic;
    prod : out std_logic_vector (31 downto 0) );
END mult_32to32;

architecture structural of mult_32to32 is

    -----
    --      Declare component: Unsinged 16 bit Multiplier
    -----

    component mult16_32
    port( au, bu: in std_logic_vector (15 downto 0);
        clk : in std_logic;
        produ : out std_logic_vector(31 downto 0));
    end component;

    -----

    -- Intermediate signals for multiplier stage
    SIGNAL    M00    :    std_logic_vector(31 downto 0);
    SIGNAL    M01    :    std_logic_vector(31 downto 0);
    SIGNAL    M10    :    std_logic_vector(31 downto 0);
    SIGNAL    M02    :    std_logic_vector(31 downto 0);
    SIGNAL    M11    :    std_logic_vector(31 downto 0);
    SIGNAL    M20    :    std_logic_vector(31 downto 0);

    -- Intermediate signals for Adding stage
    SIGNAL    A00    :    std_logic_vector(33 downto 0);
    SIGNAL    A01    :    std_logic_vector(49 downto 0);
    SIGNAL    A10    :    std_logic_vector(49 downto 0);
    SIGNAL    A02    :    std_logic_vector(65 downto 0);
    SIGNAL    A11    :    std_logic_vector(65 downto 0);
    SIGNAL    A20    :    std_logic_vector(65 downto 0);

    -- Some definitions for implementing sign extend
    SIGNAL    ae      :    std_logic_vector(15 downto 0);
    SIGNAL    be      :    std_logic_vector(15 downto 0);

```

```

-- Signal to hold value (synplify pro will not work
-- if the width is not matched, Xilinx will)
SIGNAL   prdt1 : std_logic_vector(49 downto 0);
SIGNAL   prdt2 : std_logic_vector(65 downto 0);
SIGNAL   prdt3 : std_logic_vector(65 downto 0);
SIGNAL   prdt4 : std_logic_vector(65 downto 0);
SIGNAL   prdt5 : std_logic_vector(65 downto 0);
SIGNAL   prdt6 : std_logic_vector(65 downto 0);
--SIGNAL   b      : std_logic_vector(31 downto 0);

-----
-- BEGIN the 32 bit Multiplier
-----

BEGIN

    PROCESS(clk)
        VARIABLE zer      : std_logic_vector(15 downto 0) := X"0000";
-- zeros
        VARIABLE ones     : std_logic_vector(15 downto 0) := X"FFFF";
-- ones

        BEGIN
            IF clk'event and clk = '1' THEN

                IF (a(15) = '1')THEN
                    ae(15 downto 0) <= ones;
                ELSE
                    ae(15 downto 0) <= zer;
                END IF;

                IF (b(15) = '1')THEN
                    be(15 downto 0) <= ones;
                ELSE
                    be(15 downto 0) <= zer;
                END IF;

            END IF;
        END PROCESS;

        -- Apply the Multiplies
    U00 :    mult16_32
            PORT MAP (au   (15 downto 0)=> a   (15 downto 0),
                     bu   (15 downto 0)=> b   (15 downto 0),
                     clk  => clk,
                     produ(31 downto 0)=> M00 (31 downto 0)
                     );

    U01 :    mult16_32
            PORT MAP (au   (15 downto 0)=> a   (15 downto 0),
                     bu   (15 downto 0)=> b   (31 downto 16),
                     clk  => clk,
                     produ(31 downto 0)=> M01 (31 downto 0)
                     );

    U10 :    mult16_32
            PORT MAP (au   (15 downto 0)=> a   (31 downto 16),
                     bu   (15 downto 0)=> b   (15 downto 0),

```



```

        clk                => clk,
        produ(31 downto 0)=> M10 (31 downto 0)
    );

U02 :    mult16_32
    PORT MAP (au    (15 downto 0)=> a    (15 downto 0),
              bu    (15 downto 0)=> be   (15 downto 0),
              clk    => clk,
              produ(31 downto 0)=> M02 (31 downto 0)
    );

U11 :    mult16_32
    PORT MAP (au    (15 downto 0)=> a    (31 downto 16),
              bu    (15 downto 0)=> b    (31 downto 16),
              clk    => clk,
              produ(31 downto 0)=> M11 (31 downto 0)
    );

U20 :    mult16_32
    PORT MAP (au    (15 downto 0)=> ae   (15 downto 0),
              bu    (15 downto 0)=> b    (15 downto 0),
              clk    => clk,
              produ(31 downto 0)=> M20 (31 downto 0)
    );

    -- shift the values appropriately for addition
PROCESS(clk)
BEGIN
    IF clk'event and clk = '1' then
        A00(33 downto 32) <= "00";
        A00(31 downto 0)  <= M00(31 downto 0);

        A01(49 downto 48) <= "00";
        A01(47 downto 16) <= M01(31 downto 0);
        A01(15 downto 0)  <= X"0000";

        A10(49 downto 48) <= "00";
        A10(47 downto 16) <= M10(31 downto 0);
        A10(15 downto 0)  <= X"0000";

        A02(65 downto 64) <= "00";
        A02(63 downto 32) <= M02(31 downto 0);
        A02(31 downto 0)  <= X"00000000";

        A11(65 downto 64) <= "00";
        A11(63 downto 32) <= M11(31 downto 0);
        A11(31 downto 0)  <= X"00000000";

        A20(65 downto 64) <= "00";
        A20(63 downto 32) <= M20(31 downto 0);
        A20(31 downto 0)  <= X"00000000";

        END if;
    END PROCESS;

PROCESS(clk)
BEGIN
    IF clk'event and clk = '1' then

```

```

        prdt1 <= unsigned(A00) + unsigned(A01) + unsigned(A10);
        prdt2 <= unsigned(A02) + unsigned(A11) + unsigned(A20);
        prdt3 <= unsigned(prdt2) + unsigned(prdt1);
        prod  <= prdt3(47 downto 16);
    END IF;
END PROCESS;

END structural;

```

2. Verilog

```

// $Id: S_MULT_64TO64_SRC6.v,v 1.1 2007/06/25 18:20:29 pvg Exp $

//
// Copyright 2007 SRC Computers, Inc. All Rights Reserved.
//
// Manufactured in the United States of America.
//
// SRC Computers, Inc.
// 4240 N Nevada Avenue
// Colorado Springs, CO 80907
// (v) (719) 262-0213
// (f) (719) 262-0223
//
// No permission has been granted to distribute this software
// without the express permission of SRC Computers, Inc.
//
// This program is distributed WITHOUT ANY WARRANTY OF ANY KIND.
//

// DESCRIPTION: This module performs 64 bit signed integer
multiplication
// and provides a 64 bit result.

// This module instantiates Xilinx components.
//-----//
// This file was modified by Njuguna Macaria to make a 64 bit by 64 bit
// Multiplier with a 64 bit result that is shifted to the appropriate
// decimal point for a 32 bit integer and 32 bit fraction.
//
//-----//

//-----//
//                               32 BIT MULTIPLIER                               //
//-----//

`timescale 1ns/1ns

module mult32_64s (A, B, Q, CLK, CLR);
    input  [31:0] A;
    input  [31:0] B;
    output [63:0] Q;

```

```

input  CLK  /* synthesis syn_noclockbuf=1 syn_maxfan=100000 */ ;
input  CLR;

reg    [63:0] Q;

reg    [31:0] AR;
reg    [31:0] BR;

wire   [35:0] R0;
wire   [35:0] R1;
wire   [35:0] R2;
wire   [35:0] R3;

reg    [31:0] R0_R;
reg    [31:0] R1_R;
reg    [31:0] R2_R;
reg    [31:0] R3_R;

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        AR <= 0;
        BR <= 0;
    end
    else begin
        AR <= A;
        BR <= B;
    end
end

MULT18X18S X0 (
    .A      ({2'b0, AR[15:0]}),
    .B      ({2'b0, BR[15:0]}),
    .C      (CLK),
    .R      (CLR),
    .CE      (1'b1),
    .P      (R0)
);

MULT18X18S X1 (
    .A      ({2'b0, AR[31:16]}),
    .B      ({2'b0, BR[15:0]}),
    .C      (CLK),
    .R      (CLR),
    .CE      (1'b1),
    .P      (R1)
);

MULT18X18S X2 (
    .A      ({2'b0, AR[15:0]}),
    .B      ({2'b0, BR[31:16]}),
    .C      (CLK),
    .R      (CLR),
    .CE      (1'b1),
    .P      (R2)
);

```

```

);

MULT18X18S X3 (
.A      ({2'b0, AR[31:16]}),
.B      ({2'b0, BR[31:16]}),
.C      (CLK),
.R      (CLR),
.CE     (1'b1),
.P      (R3)
);

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        R0_R <= 0;
        R1_R <= 0;
        R2_R <= 0;
        R3_R <= 0;
    end
    else begin
        R0_R <= R0;
        R1_R <= R1;
        R2_R <= R2;
        R3_R <= R3;
    end
end

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        Q <= 0;
    end
    else begin
        // add and shift
        Q <= R0_R + {R1_R,16'b0} + {R2_R,16'b0} + {R3_R,32'b0};
    end
end

endmodule

//-----//
//-----//
//          64 BIT MULTIPLIER          //
//-----//
//-----//

`timescale 1ns/1ns

module mult_64s (A, B, Q, CLK, CLR);
    input  [63:0] A;
    input  [63:0] B;
    output [63:0] Q;
    input  CLK /* synthesis syn_noclockbuf=1 syn_maxfan=100000 */ ;
    input  CLR;

```

```

reg    [127:0] Q_R;
reg    [ 63:0] Q;

reg    [63:0] AR;
reg    [63:0] BR;

wire   [63:0] R0;
wire   [63:0] R1;
wire   [63:0] R2;
wire   [63:0] R3;

reg    [63:0] R0_R;
reg    [63:0] R1_R;
reg    [63:0] R2_R;
reg    [63:0] R3_R;

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        AR <= 0;
        BR <= 0;
    end
    else begin
        AR <= A;
        BR <= B;
    end
end

mult32_64s X0 (
    .A      (AR[31:0]),
    .B      (BR[31:0]),
    .Q      (R0),
    .CLK    (CLK),
    .CLR    (CLR)
);

mult32_64s X1 (
    .A      (AR[63:32]),
    .B      (BR[31:0 ]),
    .Q      (R1),
    .CLK    (CLK),
    .CLR    (CLR)
);

mult32_64s X2 (
    .A      (AR[31:0]),
    .B      (BR[63:32]),
    .Q      (R2),
    .CLK    (CLK),
    .CLR    (CLR)
);

mult32_64s X3 (
    .A      (AR[63:32]),

```

```

.B      (BR[63:32]),
.Q      (R3),
.CLK    (CLK),
.CLR    (CLR)
);

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        R0_R <= 0;
        R1_R <= 0;
        R2_R <= 0;
        R3_R <= 0;
    end
    else begin
        R0_R <= R0;
        R1_R <= R1;
        R2_R <= R2;
        R3_R <= R3;
    end
end

always @ (posedge CLK or posedge CLR)
begin
    if (CLR) begin
        Q <= 0;
    end
    else begin
        // add and shift
        Q_R <= R0_R + {R1_R,32'b0} + {R2_R,32'b0} + {R3_R,64'b0};
        // Only take 64 bits from the middle for a 32.32 number
        Q    <= Q_R[95:32];
    end
end

endmodule

```

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APPENDIX C. SRC C CODE

C.1 UNIFORM SEGMENTATION

1. Floating Point

a. *Main.c*

```
#include<stdio.h>
#include<stdlib.h>
#include<strings.h>
#include<libmap.h>

// Subroutine initialization in Main
void subr_map( double  acoef[],
               int     ncoef,
               double  incre,
               double  offsetV,
               double  x[],
               double  y[],
               double  ys[],
               int     npts,
               int64_t *time0,
               int64_t *time1,
               int     mapnum);

// MAIN
main () {

    // Initialize Variables
    FILE      *fp1;
    double    *array, *x, *y, *ys, incre,val,offsetV;
    int       i,ir,nc,npts, mapnum,nmap, ncoef,arr_indx,inNum;
    int64_t   tm0, tm1;

    // Start NFG and select map number
    printf ("\\n***START UP THE NFG ***\\n");
    mapnum = 0;
    nmap    = 1;

    //      ! allocate map to this problem
    map_allocate (nmap);

    // User interface
    printf("-----\\n");
    printf("Function   1.  2^x                      :  1\\n");
    printf("Function   2.  1/x                      :  2\\n");
    printf("Function   3.  sqrt(x)                   :  3\\n");
    printf("Function   4.  1/sqrt(x)                  :  4\\n");
    printf("Function   5.  log2(x)                    :  5\\n");
    printf("Function   6.  ln(x)                     :  6\\n");
    printf("Function   7.  sin(pi*x)                  :  7\\n");
    printf("Function   8.  cos(pi*x)                  :  8\\n");
    printf("Function   9.  tan(pi*x)                  :  9\\n");
```



```

printf("Function 10.  sqrt(-ln(x))                : 10\n");
printf("Function 11.  tan(pi*x)^2 + 1              : 11\n");
printf("Function 12.  -(x*log2(x) + (1-x)*log2(1-x)): 12\n");
printf("Function 13.  1/(1+e^(-x))                  : 13\n");
printf("Function 14.  (1/sqrt(2*pi))*exp(-x^2/2)     : 14\n");
printf("Function 15.  sin(exp(x))                    : 15\n");
printf("-----\n");

printf("\nSelect which function to implement: ");
scanf("%i", &inNum);
printf("What value did I enter: %i \n ",inNum);

// Open the Hex data file to read
switch (inNum)
{
    case 1: fp1 = fopen("Data/memD1.mem", "r");
        break;
    case 2: fp1 = fopen("Data/memD2.mem", "r");
        break;
    case 3: fp1 = fopen("Data/memD3.mem", "r");
        break;
    case 4: fp1 = fopen("Data/memD4.mem", "r");
        break;
    case 5: fp1 = fopen("Data/memD5.mem", "r");
        break;
    case 6: fp1 = fopen("Data/memD6.mem", "r");
        break;
    case 7: fp1 = fopen("Data/memD7.mem", "r");
        break;
    case 8: fp1 = fopen("Data/memD8.mem", "r");
        break;
    case 9: fp1 = fopen("Data/memD9.mem", "r");
        break;
    case 10: fp1 = fopen("Data/memD10.mem", "r");
        break;
    case 11: fp1 = fopen("Data/memD11.mem", "r");
        break;
    case 12: fp1 = fopen("Data/memD12.mem", "r");
        break;
    case 13: fp1 = fopen("Data/memD13.mem", "r");
        break;
    case 14: fp1 = fopen("Data/memD14.mem", "r");
        break;
    default: fp1 = fopen("Data/memD15.mem", "r");
        break;
}
printf ("fp1 %i\n",fp1);

// Read in the values from the file
fscanf (fp1, "%i", &ncoef);
fscanf (fp1, "%lf", &incre);
fscanf (fp1, "%lf", &offsetV);

// Depending on number segments

```

```

//nc = 50;          // For 16 bit accuracy
//nc = 600;         // For 23 bits
//nc = 1500;        // For 32 bits
nc = 35000;         // For 40 bits
array      = (double*)Cache_Aligned_Allocate (4*nc*8);
x          = (double*)Cache_Aligned_Allocate (nc*8 );
y          = (double*)Cache_Aligned_Allocate (nc*8 );
ys         = (double*)Cache_Aligned_Allocate (nc*8 );

// check if the right thing was read
printf (" ncoef %i\n",ncoef);

// read_file
for (i=0;i<ncoef;i++) {
    fscanf (fp1, "%lf", &val);
    array[i*4] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+1] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+2] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+3] = val;
} // end read_file
fclose(fp1);

npts = 30;
// create_samples
for (ir=0;ir<npts;ir++) {
    arr_indx = ir % ncoef;
    x[ir]    = array[arr_indx*4];
    printf ("ir %3i x_values are: %lf\n",ir,x[ir]);
} //end create_samples

printf ("main ncoef %i npts %i\n",ncoef,npts);

subr_map (array, ncoef, incre, offsetV, x, y, ys, npts, &tm0, &tml,
mapnum);

printf ("\n***** BACK FROM MAP *****\n");
printf ("%lld clocks for NFG\n", tm0);
printf ("%lld clocks for SRC Macro\n", tml);

for (i=0;i<npts;i++) {
    printf ("x: %5.16lf ysubr: %5.16lf ySRCMacro: %5.16lf\n",
            x[i],y[i],ys[i] );
}

//      ! release the map resources
map_free (nmap);
}

```

b. subr.mc

```
#include <libmap.h>

void subr_map ( double  ac[],
                int      ncoef,
                double   incre,
                double   offsetV,
                double   xc[],
                double   yc[],
                double   ys[],
                int       npts,
                int64_t   *time0,
                int64_t   *time1,
                int       mapno)
{
    /*****
    *  Declarations
    *****/
    OBM_BANK_A (ysmap, double, MAX_OBM_SIZE)
    OBM_BANK_B (a, double, MAX_OBM_SIZE)
    OBM_BANK_C (b, double, MAX_OBM_SIZE)
    OBM_BANK_D (c, double, MAX_OBM_SIZE)
    OBM_BANK_E (x, double, MAX_OBM_SIZE)
    OBM_BANK_F (y, double, MAX_OBM_SIZE)
    int i,j, nbytes, indx;
    int64_t tm0,tm1;
    double varx,indxtmp;

    /*****
    *  Read in the cooeff and segment endpoints
    *****/
    nbytes = 4*ncoef * 8; /* 4 data values (seg,a,b,c), 64bits each */
    DMA_CPU (CM2OBM, ysmmap, MAP_OBM_stripe(1,"A,B,C,D"), ac, 1, nbytes,
0);
    wait_DMA (0);

    /*****
    *  Read in the Number of points
    *****/
    nbytes = npts * 8;
    DMA_CPU (CM2OBM, x, MAP_OBM_stripe(1,"E"), xc, 1, nbytes, 0);
    wait_DMA (0);

    /*****
    *  Useful in Debug Mode to determine when in Map
    *****/
    printf ("\n\n***** NOW IN MAP *****\n");
    printf ("MAP subr ncoef %i npts %i\n",ncoef,npts);

    /*****
    *  Read timer and use a constant for UNIFORM Segmentation
    *****/
    read_timer (&tm0);
}
```

```

printf("incre: %15.10lf  offset: %15.10lf\n", incre,offsetV);
for (i=0;i<npts;i++)
{
    varx      = x[i];
    indxtmp = incre * varx;
    indx      = (int)(indxtmp-offsetV);    // For interval [a,b]; when
a!=0
    y[i] = a[indx]*varx*varx + varx*b[indx] + c[indx];
    // For Debug only
    printf("indxtmp: %15.10lf indx: %i x: %15.10lf a: %15.10lf ",
           indxtmp,      indx,      varx,      a[indx]);
    printf("b: %15.10lf c: %15.10lf fx: %15.10lf\n",
           b[indx],      c[indx],      y[i]);
}

read_timer (&tml);
*time0 = tml-tm0;

read_timer (&tm0);
if(ncoef == 4017){
    for (i=0; i<npts; i++)
        ysmap[i] = sqrt(-1*logf(x[i]));        // func 10
// ysmap[i] = cosf(x[i]*3.14159265358979);    // func 8
}
read_timer (&tml);

*time1 = tml - tm0;

/*****
*   Send back the results
*****/
nbytes = npts * 8;
DMA_CPU (OBM2CM, y, MAP_OBM_stripe(1,"F"), yc, 1, nbytes, 0);
wait_DMA (0);

nbytes = npts * 8;
DMA_CPU (OBM2CM, ysmap, MAP_OBM_stripe(1,"A"), ys, 1, nbytes, 0);
wait_DMA (0);
}

```

c. Sample memory file (memD13.mem)

```

23
23.000000000000000000
0.000000000000000000
0.043477043477043474 -0.001358317312431898 0.250022142664697360 0.499999946525873650
0.086956086956086961 -0.004069869528842258 0.250257856231724860 0.499994717163829820
0.130434130434130440 -0.006766102264296870 0.250726624819223480 0.499974235918064340
0.173912173912173920 -0.009436856238895420 0.251423133697143810 0.499928719944731090
0.217390217390217380 -0.012072268340317297 0.252339521794440860 0.499848954352031030
0.260869260869260880 -0.014662753872468844 0.253465478604624370 0.499726502843754640
0.304347304347304340 -0.017199021635054011 0.254788348118468570 0.499553907045252270
0.347825347825347850 -0.019672204841648999 0.256293304836314910 0.499324864391809510
0.391303391303391310 -0.022073970679148382 0.257963583077645050 0.499034376288904240
0.434782434782434780 -0.024396553731653503 0.259780689724019740 0.498678874917245770
0.478260478260478240 -0.026632698067803585 0.261724551035193380 0.498256341372862010
0.521738521738521750 -0.028775795055367724 0.263773815334481300 0.497766372051921200
0.565216565216565270 -0.030819956163696906 0.265906159795873900 0.497210208629803470
0.608695608695608680 -0.032759983918098333 0.268098508370670290 0.496590760719450740
0.652173652173652200 -0.034591349895399928 0.270327244592241440 0.495912606692870410
0.695651695651695600 -0.036310255047355668 0.272568518769947920 0.495181941782176340
0.739129739129739120 -0.037913669840421889 0.274798561824121660 0.494406487986867260
0.782608782608782640 -0.039399282695242094 0.276993876874879700 0.493595416118664640
0.826086826086826040 -0.040765458997357298 0.279131424123494290 0.492759249956049420
0.869564869564869560 -0.042011264516131290 0.281188891968362940 0.491909715721972900
0.913042913042913070 -0.043136460147426350 0.283144934523894110 0.491059574388106770
0.956521956521956480 -0.044141446445428945 0.284979312245647760 0.490222473401396690
1.000000000000000000 -0.045027205024233290 0.286673001843708750 0.489412798087615010

```

2. Fixed Point

a. Main.c

```

#include<stdio.h>
#include<stdlib.h>
#include<strings.h>
#include<libmap.h>
#include<math.h>

// Subroutine initialization in Main
void subr_map (int64_t acoef[],
               int ncoef,
               int64_t incre,
               int64_t offsetV,
               int64_t x[],
               int64_t y[],
               int xpts,
               int64_t *time0,
               int mapnum);

// MAIN
main () {

    // Initialize Variables
    FILE *fpl;
    int i,ir,nc,xpts,inNum;
    int mapnum,nmap,ncoef;
    int arr_idx;
    int64_t *arraym,*xm,*ym,incre,offsetV;
    int64_t tm0,tml,hexval;

```

```

char    hexstr[80], *token, *stpstr, strDelimit[]=" \n";

// Starting NFG
printf ("\n***START UP THE NFG ***\n");
mapnum = 0;
nmap    = 1;

// User interface
printf("-----\n");
printf("Function    1.  2^x                               :  1\n");
printf("Function    2.  1/x                               :  2\n");
printf("Function    3.  sqrt(x)                             :  3\n");
printf("Function    4.  1/sqrt(x)                             :  4\n");
printf("Function    5.  log2(x)                               :  5\n");
printf("Function    6.  ln(x)                                 :  6\n");
printf("Function    7.  sin(pi*x)                             :  7\n");
printf("Function    8.  cos(pi*x)                             :  8\n");
printf("Function    9.  tan(pi*x)                             :  9\n");
printf("Function   10.  sqrt(-ln(x))                           : 10\n");
printf("Function   11.  tan(pi*x)^2 + 1                         : 11\n");
printf("Function   12.  -(x*log2(x) + (1-x)*log2(1-x))          : 12\n");
printf("Function   13.  1/(1+e^(-x))                           : 13\n");
printf("Function   14.  (1/sqrt(2*pi))*exp(-x^2/2)              : 14\n");
printf("Function   15.  sin(exp(x))                             : 15\n");
printf("-----\n");

//inNum = 1;          // dummy default value
printf("\nSelect which function to implement: ");
scanf("%i", &inNum);
printf("What value did I enter: %i \n ",inNum);

// Open the Hex data file to read
switch (inNum)
{
case 1: fp1 = fopen("Data/memH1.mem", "r");
break;
case 2: fp1 = fopen("Data/memH2.mem", "r");
break;
case 3: fp1 = fopen("Data/memH3.mem", "r");
break;
case 4: fp1 = fopen("Data/memH4.mem", "r");
break;
case 5: fp1 = fopen("Data/memH5.mem", "r");
break;
case 6: fp1 = fopen("Data/memH6.mem", "r");
break;
case 7: fp1 = fopen("Data/memH7.mem", "r");
break;
case 8: fp1 = fopen("Data/memH8.mem", "r");
break;
case 9: fp1 = fopen("Data/memH9.mem", "r");
break;
}

```

```

case 10: fp1 = fopen("Data/memH10.mem","r");
        break;
case 11: fp1 = fopen("Data/memH11.mem","r");
        break;
case 12: fp1 = fopen("Data/memH12.mem","r");
        break;
case 13: fp1 = fopen("Data/memH13.mem","r");
        break;
case 14: fp1 = fopen("Data/memH14.mem","r");
        break;
default: fp1 = fopen("Data/memH15.mem","r");
        break;
}
printf ("fp1 %i\n",fp1);

// ! allocate map to this problem
map_allocate (nmap);

// Read in the number of segments (decimal #)
fscanf (fp1, "%i", &ncoef);
fscanf (fp1, "%llx", &incre);
fscanf (fp1, "%llx", &offsetV);
printf ("ncoef: %3i incre: %8llx\n",ncoef,incre);

// Accommodate lots of resutls
nc = 30000;

// array is enough room to hold 4 64 bit data pieces
// Perform cache alignment
arraym = (int64_t *)Cache_Aligned_Allocate (4*ncoef*8);
xm      = (int64_t *)Cache_Aligned_Allocate (nc*8 );
ym      = (int64_t *)Cache_Aligned_Allocate (nc*8 );

// Get rid of first npc
fgets (hexstr, sizeof hexstr, fp1);

// Read all endpoints and coefficients into OBM banks
for (i=0;i<ncoef;i++) {
    fgets (hexstr, sizeof hexstr, fp1);

    token      = strtok(hexstr,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+1] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+2] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+3] = hexval;
}

```

```

}

// close the file
fclose(fp1);

// create some values to test with
xpts = 100;
for (ir=0;ir<xpts;ir++) {
    arr_indx = ir % ncoef;
    xm[ir] = arraym[arr_indx*4];          // Optional -0x2061d;
    printf ("arr_indx = %3i  xm[%2i]= %10llx\n",
            arr_indx,  ir, xm[ir]);
}

printf ("Right Before MAP *** \nmain ncoef %i xpts %i\n",
        ncoef,  xpts);
subr_map (arraym,ncoef,incre,offsetV,xm,ym,xpts,&tm0,mapnum);

printf ("\n*****Back from the MAP!!!*****\n");
printf ("\n*****SHIFT8 *****\n");
printf ("%lld clocks\n", tm0);
for(i=0;i<xpts;i++){
    printf ("i: %3i x: %8llx fx: %10llx\n",i,xm[i],ym[i] );
}
printf ("%lld clocks\n", tm1);

//      ! release the map resources
map_free (nmap);
}

```

b. subr.mc

```

#include <libmap.h>

void subr_map (int64_t  ac[],
               int      ncoef,
               int64_t  incre,
               int64_t  offsetV,
               int64_t  xc[],
               int64_t  yc[],
               int      xpts,
               int64_t  *time0,
               int      mapno) {

    /*****
    *  Declarations
    *****/
    OBM_BANK_A (segend, int64_t, MAX_OBM_SIZE)
    OBM_BANK_B (a,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_C (b,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_D (c,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_E (x,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_F (y,      int64_t, MAX_OBM_SIZE)
    int        i,j, nbytes;

```



```

int64_t    tm0,tm1,varx,varsq,vara,varb,varc,ax2,bx1,fx;
int64_t    varxtmp,indx;

/*****
*   Read into OBM. Cooeff & segment endpoints *
*****/

// 4 data values (seg,a,b,c), 64bit Hex values
nbytes = 4*ncoef * 8;
DMA_CPU(CM2OBM,segend,MAP_OBM_stripe(1,"A,B,C,D"),ac,1,nbytes, 0);
wait_DMA (0);

// Read in the Number of points
nbytes = xpts * 8;
DMA_CPU (CM2OBM, x, MAP_OBM_stripe(1,"E"), xc, 1, nbytes, 0);
wait_DMA (0);

// DEBUG: determine when in Map
printf ("\n\n***** NOW IN MAP *****\n");
printf ("MAP subr ncoef %i xpts %i \n",ncoef,xpts);

/*****
*   Read timer and use selector to determine the segment *
*****/
read_timer (&tm0);

incre     >>= 16;           // asr to open integer bits
offsetV >>= 16;           // asr to match in subtraction

for (i=0;i<xpts;i++)
{
    varx     = x[i];           // Take from OBM put in BRAM
    indx     = varx * incre;    // Segment index Number * x input
    indx     >>= 32;           // Return to 16 fraction points
    indx     = indx - offsetV;  // Adjust index to interval start
    indx     >>= 16;           // remove fracion
    vara     = a[(int)indx];    // Move from OBM into BRAM
    varb     = b[(int)indx];
    varc     = c[(int)indx];

    // ----- Square X and shift ----//
    varx     >>= 8;           // Remove lower 8 bits, 40.24
    varsq    = varx*varx;      // Now we have 80.48 -> 16.48
    varsq    >>= 24;           // SRL eliminate 40.24
    if (varx < 0x8000000000000000) // if varx is positive
        varsq = varsq & 0x000000FFFFFFFF; // bitwise AND; 24bits

    // --- X^2 * first Coefficient ---//
    vara     >>= 8;           // remove lower 8 bits, 40.24
    ax2      = varsq*vara;     // a[indx];
    ax2      >>= 16;           // Want 32.32, so srl 16
    if (vara < 0x8000000000000000) // if both +ve
        ax2 = ax2 & 0x0000FFFFFFFF; // bitwise AND; 16bits

```

```

// --- X * second Coefficient ---//
varb >>= 8; // Remove lower 8 bits, 40.24
bx1 = varx*varb; // both are already shifted
bx1 >>= 16; // Return to 32.32 (int.fract)
if (varb < 0x8000000000000000) // if both +ve
    bx1 = bx1 & 0x0000FFFFFFFFFFFF; // bitwise AND; 16bits

// -- 3 input add to complete ---//
y[i] = ax2+bx1+varc; // no need to shift varc

// DEBUG
// printf("indx: %4llx -> %4li varx: %6llx incre: %6llx\n",
//         indx, (int)indx,varx, incre);
}

// Time it took to compute
read_timer (&tml);
*time0 = tml-tm0;

/*****
* Send back the results
*****/
nbytes = xpts * 8;
DMA_CPU (OBM2CM, y, MAP_OBM_stripe(1,"F"), yc, 1, nbytes, 0);
wait_DMA (0);
}

```

C.2 NON-UNIFORM SEGMENTATION

1. Floating Point

a. *Main.c*

```
#include<stdio.h>
#include<stdlib.h>
#include<strings.h>
#include<libmap.h>

// Subroutine initialization in Main
void subr_map( double  acoef[],
               int     ncoef,
               double  x[],
               double  y[],
               double  ys[],
               int     npts,
               int64_t *time0,
               int64_t *time1,
               int     mapnum);

// MAIN
main ()  {

    // Initialize Variables
    FILE      *fp1;
    double    *array, *x, *y, *ys;
    double    val;
    int       i,ir,nc,npts, mapnum,nmap, ncoef,arr_indx;
    int64_t   tm0, tml;

    printf ("\\n***START UP THE NFG ***\\n");

    // select map number
    mapnum = 0;
    nmap   = 1;

    //      ! allocate map to this problem
    map_allocate (nmap);

    // Depending on number segments
    //nc = 50;      // For 16 bit accuracy
    nc = 200;     // For 23 bits
    //nc = 1500;    // For 32 bits
    //nc = 5000;    // For 42 bits
    array      = (double*)Cache_Aligned_Allocate (4*nc*8);
    x          = (double*)Cache_Aligned_Allocate (nc*8 );
    y          = (double*)Cache_Aligned_Allocate (nc*8 );
    ys         = (double*)Cache_Aligned_Allocate (nc*8 );

    fp1 = fopen ("Data/memDEC.mem","r");
    fscanf (fp1, "%i", &ncoef);
    // check if the right thing was read
    printf ("  ncoef    %i\\n",ncoef);
```

```

// read_file
for (i=0;i<ncoef;i++) {
    fscanf (fp1, "%lf", &val);
    array[i*4] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+1] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+2] = val;

    fscanf (fp1, "%lf", &val);
    array[i*4+3] = val;
} // end read_file

/* // print_array
for (i=0;i<ncoef;i++) {
    printf (" endpt %10.6f a %10.6f b %10.6f c %10.6f\n",
        array[4*i+0],
        array[4*i+1],
        array[4*i+2],
        array[4*i+3]);
} // end print_array
*/

npts = 100;
// create_samples
for (ir=0;ir<npts;ir++) {
    arr_indx = ir % ncoef;
    x[ir] = array[arr_indx*4];
    printf ("ir %3i x_values are: %lf\n",ir,x[ir]);
} //end create_samples

printf ("main ncoef %i npts %i\n",ncoef,npts);

subr_map (array, ncoef, x, y, ys, npts, &tm0, &tml, mapnum);

printf ("\n***** BACK FROM MAP *****\n");
printf ("%lld clocks\n", tm0);
printf ("%lld clocks\n", tml);

for (i=0;i<npts;i++) {
    printf ("x: %5.18lf ysubr: %5.18lf SRCMacro2^x: %5.18f\n",
        x[i], y[i], ys[i]);
// printf ("x: %5.18f ysubr: %5.18f\n",x[i],y[i]);
}

// ! release the map resources
map_free (nmap);
}

```

b. *subr.mc* $\left(\frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} \right)$

```
#include <libmap.h>

void subr_map ( double  ac[],
                int      ncoef,
                double  xc[],
                double  yc[],
                double  ys[],
                int      npts,
                int64_t  *time0,
                int64_t  *time1,
                int      mapno)
{
    /*****
    *  Declarations
    *****/
    OBM_BANK_A (ysmap, double, MAX_OBM_SIZE)
    OBM_BANK_B (a, double, MAX_OBM_SIZE)
    OBM_BANK_C (b, double, MAX_OBM_SIZE)
    OBM_BANK_D (c, double, MAX_OBM_SIZE)
    OBM_BANK_E (x, double, MAX_OBM_SIZE)
    OBM_BANK_F (y, double, MAX_OBM_SIZE)
    int i,j, nbytes, indx, sel;
    int64_t tm0,tml;
    double varx;

    /*****
    *  Read in the cooeff and segment endpoints
    *****/
    nbytes = 4*ncoef * 8; /* 4 data values (seg,a,b,c), 64bits each */
    DMA_CPU (CM2OBM, ysmap, MAP_OBM_stripe(1,"A,B,C,D"), ac, 1, nbytes,
0);
    wait_DMA (0);

    /*****
    *  Read in the Number of points
    *****/
    nbytes = npts * 8;
    DMA_CPU (CM2OBM, x, MAP_OBM_stripe(1,"E"), xc, 1, nbytes, 0);
    wait_DMA (0);

    /*****
    *  Useful in Debug Mode to determine when in Map
    *****/
    printf ("\n\n***** NOW IN MAP *****\n");
    printf ("MAP subr ncoef %i npts %i\n",ncoef,npts);

    /*****
    *  Read timer and use a constant for UNIFORM Segmentation
    *****/
    read_timer (&tm0);
```

```

for (i=0;i<npts;i++)
{
    varx = x[i];

    if ( varx <= 1.010456600772177400)
        sel = 1;
    else if ( varx <= 1.254138569173091300)
        sel = 2;
    else if ( varx <= 1.393018722518969900)
        sel = 3;
    else if ( varx <= 1.414213562373095100)
        sel = 4;
    switch (sel)
    {
        case 1:
            select_pri_64bit_32val(  varx <= 0.065896761049097793,    0,
                                     varx <= 0.113411555832503830,    1,
                                     varx <= 0.155068672182882060,    2,
                                     varx <= 0.193392483833442240,    3,
                                     varx <= 0.229466279456250750,    4,
                                     varx <= 0.263888271986404410,    5,
                                     varx <= 0.297033228392699020,    6,
                                     varx <= 0.329159950015850300,    7,
                                     varx <= 0.360453699017791120,    8,
                                     varx <= 0.391055896896180420,    9,
                                     varx <= 0.421076852419192020,   10,
                                     varx <= 0.450608489560304140,   11,
                                     varx <= 0.479725761713275970,   12,
                                     varx <= 0.508490894337077280,   13,
                                     varx <= 0.536959041815795230,   14,
                                     varx <= 0.565178287458633520,   15,
                                     varx <= 0.593191057714890110,   16,
                                     varx <= 0.621035536388932610,   17,
                                     varx <= 0.648747078855175910,   18,
                                     varx <= 0.676359626273058010,   19,
                                     varx <= 0.703904291372063890,   20,
                                     varx <= 0.731409358451725390,   21,
                                     varx <= 0.758903111811573990,   22,
                                     varx <= 0.786413835751141770,   23,
                                     varx <= 0.813969814569960310,   24,
                                     varx <= 0.841596504137608230,   25,
                                     varx <= 0.869322188753617440,   26,
                                     varx <= 0.897175152717519460,   27,
                                     varx <= 0.925183680328846240,   28,
                                     varx <= 0.953378884317082620,   29,
                                     varx <= 0.981791877411713590,   30,
                                     31,    &indx);

            break;
        case 2:

            select_pri_64bit_8val(  varx <= 1.039409823987864900,   32,
                                   varx <= 1.068692559293097600,   33,

```

```

varx <= 1.098347233137172600, 34,
varx <= 1.128421928829294700, 35,
varx <= 1.158970386538573600, 36,
varx <= 1.190056245938955900, 37,
varx <= 1.221750217779271400, 38,
                                39, &indx);

break;
case 3:

select_pri_64bit_4val( varx <= 1.287320295168777200, 40,
                        varx <= 1.321418432469292400, 41,
                        varx <= 1.356585716292107800, 42,
                                43, &indx);

break;
case 4:

select_pri_64bit_4val( varx <= 1.414213562373095100, 44,
                        varx <= 1.414213562373095100, 44,
                        varx <= 1.414213562373095100, 44,
                                44, &indx);

break;
}

y[i] = a[indx]*varx*varx + varx*b[indx] + c[indx];
// printf ("i %3i a %f b %f c %f x %20.18f y %20.18f\n",
//         indx,a[indx],b[indx],c[indx],varx,y[i]);
}

read_timer (&tml);
*time0 = tml-tm0;

read_timer (&tm0);
// Function 1
for (i=0; i<npts; i++)
    ysmap[i] = (1/sqrtf(2*3.14159265258979))*powf(2.71828182845905,-
0.5*powf(x[i],2)); // func 14

//ysmap[i] = powf(2,x[i]); // func 1
//ysmap[i] = 1/x[i]; // func 2
//ysmap[i] = sqrtf(x[i]); // func 3
//ysmap[i] = 1/sqrtf(x[i]); // func 4
//ysmap[i] = logf(x[i])/0.693147180559945; // func 5
//ysmap[i] = logf(x[i]); // func 6
//ysmap[i] = sinf(x[i]*3.14159265258979); // func 7
//ysmap[i] = cosf(x[i]*3.14159265258979); // func 8
//ysmap[i] = tanf(x[i]*3.14159265258979); // func 9
//ysmap[i] = sqrt(-1*logf(x[i])); // func 10
//ysmap[i] = powf(tanf(x[i]*3.14159265258979),2); // func 11
//ysmap[i] = -(x[i]*logf(x[i])/0.69314718055994 +(1-x[i])*logf(1-
x[i])/0.69314718055994 );// func 12
//ysmap[i] = 1/(1+powf(0.693147180559945,(-1*x[i]))); // func 13
//ysmap[i] = (1/sqrtf(2*3.14159265258979))*powf(2.71828182845905,-
0.5*powf(x[i],2)); // func 14

```

```

//ysmap[i] = sinf(powf(2.71828182845905,x[i])); // func 15
    read_timer (&tml);

    *time1 = tml - tm0;

    /*****
    *   Send back the results
    *****/
    nbytes = npts * 8;
    DMA_CPU (OBM2CM, y, MAP_OBM_stripe(1,"F"), yc, 1, nbytes, 0);
    wait_DMA (0);

    nbytes = npts * 8;
    DMA_CPU (OBM2CM, ysmap, MAP_OBM_stripe(1,"A"), ys, 1, nbytes, 0);
    wait_DMA (0);
}

```

2. Fixed Point

a. *Main.c*

```

#include<stdio.h>
#include<stdlib.h>
#include<strings.h>
#include<libmap.h>
#include<math.h>

// Subroutine initialization in Main
void subr_map (int64_t acoef[],
               int ncoef,
               int64_t x[],
               int64_t y[],
               int xpts,
               int64_t *time0,
               int mapnum);

// MAIN
main () {

    // Initialize Variables
    FILE *fp1;
    int i,ir,nc,xpts;
    int mapnum,nmap,ncoef;
    int arr_indx;
    int64_t *arraym,*xm,*ym;
    int64_t tm0,tml,hexval;
    char hexstr[80], *token, *stpstr, strDelimit[]=" \n";

    // Starting NFG
    printf ("\n***START UP THE NFG ***\n");
    mapnum = 0;
    nmap = 1;

```



```

// ! allocate map to this problem
map_allocate (nmap);
nc = 300;

// array is enough room to hold 4 64 bit data pieces
// Perform cache allignment
arraym = (int64_t *)Cache_Aligned_Allocate (4*nc*8);
xm      = (int64_t *)Cache_Aligned_Allocate (nc*8 );
ym      = (int64_t *)Cache_Aligned_Allocate (nc*8 );

// Open the Hex data file to read
fp1     = fopen ("Data/memHEX0x.mem","r");
printf ("fp1 %i\n",fp1);

// Read in the number of segments (decimal #)
fscanf (fp1, "%i", &ncoef);
printf (" ncoef %i\n",ncoef);

// Get rid of first npc
fgets (hexstr, sizeof hexstr, fp1);

// Read all endpoints and coefficients into OBM banks
for (i=0;i<ncoef;i++) {
    fgets (hexstr, sizeof hexstr, fp1);

    token      = strtok(hexstr,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+1] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+2] = hexval;

    token = strtok(NULL,strDelimit);
    sscanf (token, "%llx", &hexval);
    arraym[i*4+3] = hexval;
}
fclose(fp1);
/*
// print out the contents of the array first 30 elements only
for (i=0;i<30;i++) {
    printf ("endpoint: %llx a: %llx b: %llx c: %llx \n",
        arraym[i*4],arraym[i*4+1],arraym[i*4+2],arraym[i*4+3]);
}
*/
// create some values to test with
xpts = 30;
for (ir=0;ir<xpts;ir++) {
    //arr_indx = (int) fabs(remainder(ir,20));
    arr_indx = ir % ncoef;
    xm[ir] = arraym[arr_indx*4]; //+0xa0000000;
}

```

```

        printf ("arr_indx = %d  xm[%d]= %llx\n",arr_indx,ir,xm[ir]);
    }

    printf ("Right Before MAP *** \nmain ncoef %i xpts
%i\n",ncoef,xpts);
    subr_map (arraym, ncoef, xm, ym, xpts, &tm0, mapnum);

    printf ("\n*****Back from the MAP!!!***** \n");
    printf ("%lld clocks\n", tm0);
    for(i=0;i<xpts;i++){
    printf ("i: %3d x values: %16llx y values: %16llx \n",
            i, xm[i], ym[i]);
    }

    // ! release the map resources
    map_free (nmap);
}

```

b. subr.mc

```

#include <libmap.h>

void subr_map (int64_t ac[],
               int ncoef,
               int64_t xc[],
               int64_t yc[],
               int xpts,
               int64_t *time0,
               int mapno) {

    /*****
    * Declarations
    *****/
    OBM_BANK_A (segend, int64_t, MAX_OBM_SIZE)
    OBM_BANK_B (a, int64_t, MAX_OBM_SIZE)
    OBM_BANK_C (b, int64_t, MAX_OBM_SIZE)
    OBM_BANK_D (c, int64_t, MAX_OBM_SIZE)
    OBM_BANK_E (x, int64_t, MAX_OBM_SIZE)
    OBM_BANK_F (y, int64_t, MAX_OBM_SIZE)
    int i,j, nbytes, sel;
    int64_t tm0,tml,indx,varx,varsq,vara,varb,varc,ax2,bx1,fx;

    /*****
    * Read into OBM. Cooeff & segment endpoints *
    *****/

    // 4 data values (seg,a,b,c), 64bit Hex values
    nbytes = 4*ncoef * 8;
    DMA_CPU (CM2OBM, segend, MAP_OBM_stripe(1,"A,B,C,D"), ac, 1,
nbytes, 0);
    wait_DMA (0);

    // Read in the Number of points
    nbytes = xpts * 8;
    DMA_CPU (CM2OBM, x, MAP_OBM_stripe(1,"E"), xc, 1, nbytes, 0);

```

```

wait_DMA (0);

//  DEBUG:  determine when in Map
printf ("\n\n***** NOW IN MAP *****\n");
printf ("MAP subr ncoef %i xpts %i \n",ncoef,xpts);

/*****
*  Read timer and use selector to determine the segment  *
*****/
read_timer (&tm0);
for (i=0;i<xpts;i++)
{
    varx = x[i];

    if ( varx <= 0x000000001816a7a6)
        sel = 1;
    else if ( varx <= 0x000000003b3b34a8)
        sel = 2;
    else if ( varx <= 0x0000000040000000)
        sel = 3;

    switch (sel)
    {
        case 1:
            select_pri_64bit_128val( varx <= 0x0000000000841cdf,    0,
                                     varx <= 0x0000000000885b08,    1,
                                     varx <= 0x00000000008cbea6,    2,
                                     varx <= 0x000000000091438e,    3,
                                     varx <= 0x000000000095edeb,    4,
                                     varx <= 0x00000000009abdbc,    5,
                                     varx <= 0x00000000009fb301,    6,
                                     varx <= 0x0000000000a4dle3,    7,
                                     varx <= 0x0000000000aala64,    8,
                                     varx <= 0x0000000000af8c81,    9,
                                     varx <= 0x0000000000b5283d,   10,
                                     varx <= 0x0000000000baf1bf,   11,
                                     varx <= 0x0000000000c0e908,   12,
                                     varx <= 0x0000000000c71241,   13,
                                     varx <= 0x0000000000cd6d6a,   14,
                                     varx <= 0x0000000000d3fa84,   15,
                                     varx <= 0x0000000000dabdb8,   16,
                                     varx <= 0x0000000000e1b705,   17,
                                     varx <= 0x0000000000e8e66b,   18,
                                     varx <= 0x0000000000f05015,   19,
                                     varx <= 0x0000000000f7f401,   20,
                                     varx <= 0x0000000000ffd65a,   21,
                                     varx <= 0x000000000107f71f,   22,
                                     varx <= 0x0000000001105651,   23,
                                     varx <= 0x000000000118f818,   24,
                                     varx <= 0x000000000121e09e,   25,
                                     varx <= 0x00000000012b0fe3,   26,
                                     varx <= 0x00000000013485e7,   27,
                                     varx <= 0x00000000013e46d4,   28,
                                     varx <= 0x00000000014856d2,   29,

```

```

varx <= 0x000000000152b5e2, 30,
varx <= 0x00000000015d6404, 31,
varx <= 0x000000000168698a, 32,
varx <= 0x000000000173c675, 33,
varx <= 0x00000000017f7ac4, 34,
varx <= 0x00000000018b8aa1, 35,
varx <= 0x000000000197fa35, 36,
varx <= 0x0000000001a4cda9, 37,
varx <= 0x0000000001b204fe, 38,
varx <= 0x0000000001bfa45d, 39,
varx <= 0x0000000001cdabc6, 40,
varx <= 0x0000000001dc238b, 41,
varx <= 0x0000000001eb0bad, 42,
varx <= 0x0000000001fa6855, 43,
varx <= 0x00000000020a3dac, 44,
varx <= 0x00000000021a8fdc, 45,
varx <= 0x00000000022b5ee4, 46,
varx <= 0x00000000023cb318, 47,
varx <= 0x00000000024e8c77, 48,
varx <= 0x000000000260ef2a, 49,
varx <= 0x000000000273e386, 50,
varx <= 0x0000000002876988, 51,
varx <= 0x00000000029b8985, 52,
varx <= 0x0000000002b0437b, 53,
varx <= 0x0000000002c59fbf, 54,
varx <= 0x0000000002db9e4f, 55,
varx <= 0x0000000002f2477f, 56,
varx <= 0x0000000003099f78, 57,
varx <= 0x000000000321ae8c, 58,
varx <= 0x00000000033a74bc, 59,
varx <= 0x000000000353fa5a, 60,
varx <= 0x00000000036e4390, 61,
varx <= 0x00000000038958b0, 62,
varx <= 0x0000000003a539bb, 63,
varx <= 0x0000000003c1f32c, 64,
varx <= 0x0000000003df892d, 65,
varx <= 0x0000000003fdffe7, 66,
varx <= 0x00000000041d5fac, 67,
varx <= 0x00000000043db0d1, 68,
varx <= 0x00000000045efba6, 69,
varx <= 0x0000000004814457, 70,
varx <= 0x0000000004a48f0b, 71,
varx <= 0x0000000004c8e83f, 72,
varx <= 0x0000000004ee541c, 73,
varx <= 0x000000000514df1f, 74,
varx <= 0x00000000053c8d71, 75,
varx <= 0x0000000005656765, 76,
varx <= 0x00000000058f7975, 77,
varx <= 0x0000000005bac7cd, 78,
varx <= 0x0000000005e75ee8, 79,
varx <= 0x0000000006154718, 80,
varx <= 0x00000000064488b1, 81,
varx <= 0x000000000675302f, 82,
varx <= 0x0000000006a745e3, 83,
varx <= 0x0000000006dad222, 84,

```

```

varx <= 0x00000000070fe58f, 85,
varx <= 0x0000000007468456, 86,
varx <= 0x00000000077ebf1a, 87,
varx <= 0x0000000007b89e30, 88,
varx <= 0x0000000007f42e12, 89,
varx <= 0x0000000008317b3d, 90,
varx <= 0x000000000870922d, 91,
varx <= 0x0000000008b17f5e, 92,
varx <= 0x0000000008f45375, 93,
varx <= 0x00000000093916c6, 94,
varx <= 0x00000000097fd9f5, 95,
varx <= 0x0000000009c8a97f, 96,
varx <= 0x000000000a139609, 97,
varx <= 0x000000000a60b038, 98,
varx <= 0x000000000ab00489, 99,
varx <= 0x000000000b01a3a1, 100,
varx <= 0x000000000b559e25, 101,
varx <= 0x000000000bac04bb, 102,
varx <= 0x000000000c04e808, 103,
varx <= 0x000000000c605cdb, 104,
varx <= 0x000000000cbe6fb0, 105,
varx <= 0x000000000d1f3980, 106,
varx <= 0x000000000d82c6c5, 107,
varx <= 0x000000000de93079, 108,
varx <= 0x000000000e528741, 109,
varx <= 0x000000000ebedfeb, 110,
varx <= 0x000000000f2e5370, 111,
varx <= 0x000000000fa0f275, 112,
varx <= 0x0000000001016d5f3, 113,
varx <= 0x000000000109016e0, 114,
varx <= 0x000000000110cca0d, 115,
varx <= 0x000000000118d0871, 116,
varx <= 0x0000000001210e6db, 117,
varx <= 0x0000000001298826c, 118,
varx <= 0x0000000001323f41d, 119,
varx <= 0x00000000013b3590f, 120,
varx <= 0x0000000001446c611, 121,
varx <= 0x00000000014de5c6e, 122,
varx <= 0x000000000157a3947, 123,
varx <= 0x000000000161a7594, 124,
varx <= 0x00000000016bf32a0, 125,
varx <= 0x00000000017688d8d, 126,
                                127, &indx);

break;
case 2:

select_pri_64bit_32val( varx <= 0x00000000018c9a234, 128,
varx <= 0x00000000019819a5b, 129,
varx <= 0x0000000001a3eb58d, 130,
varx <= 0x0000000001b01193f, 131,
varx <= 0x0000000001bc8e294, 132,
varx <= 0x0000000001c963b27, 133,
varx <= 0x0000000001d694444, 134,
varx <= 0x0000000001e422789, 135,
varx <= 0x0000000001f210a6a, 136,

```

```

varx <= 0x0000000020061683, 137,
varx <= 0x0000000020f17574, 138,
varx <= 0x0000000021e350d9, 139,
varx <= 0x0000000022dbd679, 140,
varx <= 0x0000000023db2ff2, 141,
varx <= 0x0000000024e18b0b, 142,
varx <= 0x0000000025ef158a, 143,
varx <= 0x000000002703fd37, 144,
varx <= 0x0000000028207402, 145,
varx <= 0x000000002944a7b1, 146,
varx <= 0x000000002a70ce5e, 147,
varx <= 0x000000002ba519fa, 148,
varx <= 0x000000002celc09e, 149,
varx <= 0x000000002e26f43b, 150,
varx <= 0x000000002f74ef13, 151,
varx <= 0x0000000030cbe73f, 152,
varx <= 0x00000000322c12da, 153,
varx <= 0x000000003395ac27, 154,
varx <= 0x000000003508f191, 155,
varx <= 0x0000000036861933, 156,
varx <= 0x00000000380d5d4f, 157,
varx <= 0x00000000399efc52, 158,
                                159, &indx);

break;
case 3:

select_pri_64bit_4val( varx <= 0x000000003ce244bd, 160,
varx <= 0x000000003e9466d5, 161,
varx <= 0x0000000040000000, 162,
                                162, &indx);

break;
}

// ----- Shift by 8 bits - -----//
vara    = a[indx];
varb    = b[indx];
varx >>= 8;      // Shift right 8 for mult 40.24
vara >>= 8;      // Shift right 8
varb >>= 8;      // Shift right 8

// ----- Square X and shift ----//
varsq   = varx*varx;      // Now we have 80.48 -> 16.48
varsq >>= 24;      // SRL eliminate 40.24
varsq   = varsq & 0x000000FFFFFFFF; // bitwise AND; 24bits

// -- X^2 * first Coefficient --//
ax2     = varsq*vara;      // a[indx];
ax2 >>= 16;      // Want 32.32, so srl 16
if (vara < 0x8000000000000000) // if both +ve
    ax2 = ax2 & 0x0000FFFFFFFF; // bitwise AND; 16bits

// --- X * second Coefficient ---//
bx1     = varx*varb;      // both are already shifted
bx1 >>= 16;      // Return to 32.32 (int.fract)

```

```

        if (varb < 0x8000000000000000) // if both +ve
            bx1 = bx1 & 0x0000FFFFFFFFFFFF; // bitwise AND; 16bits

        // -- 3 input add to complete --//
        y[i] = ax2+bx1+c[indx]; // Add all, no need to shift varc

        // DEBUG: printf for debug information on variable status
        printf ("indx: %3i, varx: %8llx vasq: %10llx a: %10llx ax2:
%16llx b: %16llx bx1: %16llx c: %10llx fx: %16llx \n",
            (int)indx, varx, varsq, vara, ax2,
            varb, bx1, c[indx], y[i]);

    }

    // Time it took to compute
    read_timer (&tml);
    *time0 = tml-tm0;

    /*****
    * Send back the results
    *****/
    nbytes = xpts * 8;
    DMA_CPU (OBM2CM, y, MAP_OBM_stripe(1,"F"), yc, 1, nbytes, 0);
    wait_DMA (0);
}

```

3. Fixed Point with Macro

This implementation did not produce the correct values. The multiplier macro used in this case was the VHDL macro shown in Appendix B.

The user can add macros to the *Makefile* that are coded in VHDL, Verilog or in both description languages. Here we show two VHDL files added to the *Makefile* and the *blk.v* and *info* files.

a. Makefile

```

# $Id: Makefile,v 2.0.0.1 2005/06/10 23:12:59 hammes Exp $
#
# Copyright 2003 SRC Computers, Inc. All Rights Reserved.
#
# Manufactured in the United States of America.
#
# SRC Computers, Inc.
# 4240 N Nevada Avenue
# Colorado Springs, CO 80907
# (v) (719) 262-0213
# (f) (719) 262-0223

```

```

#
# No permission has been granted to distribute this software
# without the express permission of SRC Computers, Inc.
#
# This program is distributed WITHOUT ANY WARRANTY OF ANY KIND.
#
# -----
# -----
# User defines FILES, MAPFILES, and BIN here
# -----
FILES          = main.c

MAPFILES       = subr.mc

BIN            = nfg

# -----
# Multi chip info provided here
# (Leave commented out if not used)
# -----
#PRIMARY       = <primary file 1>   <primary file 2>

#SECONDARY     = <secondary file 1> <secondary file 2>

#CHIP2         = <file to compile to user chip 2>

#-----
# User defined directory of code routines
# that are to be inlined
#-----

#INLINEDIR    =

# -----
# User defined macros info supplied here
#
# (Leave commented out if not used)
# -----

#MACROS        = my_macro1/mult_vrlg_64.v
#MY_BLKBOX     = my_macro1/blk.v
#MY_NGO_DIR    = my_macro1
#MY_INFO       = my_macro1/info

MACROS        = my_macro/mult_32to32.vhd \
               my_macro/add_32.vhd
MY_BLKBOX     = my_macro/blk.v
MY_NGO_DIR    = my_macro
MY_INFO       = my_macro/info

# -----
# Floating point macros selection
# -----

```



```

#FPMODE      = SRC_IEEE_V1 # Default SRC version IEEE
#FPMODE      = SRC_IEEE_V2 # Size reduced SRC IEEE with
                        # special rounding mode
# -----
# User supplied MCC and MFTN flags
# -----

MCCFLAGS     = -log -explain_dep -g -keep -use_par
MFTNFLAGS    = -log -v

# -----
# User supplied flags for C & Fortran compilers
# -----

CC           = icc      # icc      for Intel cc for Gnu
FC           = ifort    # ifort    for Intel f77 for Gnu
LD           = icc      # for C codes
#LD          = ifort    # for Fortran or C/Fortran mixed

CFLAGS       =
FFLAGS       =
LDLFLAGS     = # Flags to include libs if needed
# -----
# VCS simulation settings
# (Set as needed, otherwise just leave commented out)
# -----

#USEVCS      = yes      # YES or yes to use vcs instead of vcsci
#VCS_DUMP    = yes      # YES or yes to generate vcd+ trace dump
# -----
# No modifications are required below
# -----
MAKIN        ?= $(MC_ROOT)/opt/src-ci/comp/lib/AppRules.make
include $(MAKIN)

```

b. subr.mc

```

#include <libmap.h>

void subr_map (int64_t  ac[],
               int      ncoef,
               int64_t  xc[],
               int64_t  yc[],
               int      xpts,
               int64_t  *time0,
               int      mapno) {

    /*****
    *  Declarations
    *****/
    OBM_BANK_A (segend, int64_t, MAX_OBM_SIZE)
    OBM_BANK_B (a,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_C (b,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_D (c,      int64_t, MAX_OBM_SIZE)
    OBM_BANK_E (x,      int64_t, MAX_OBM_SIZE)

```

```

OBM_BANK_F (y,      int64_t, MAX_OBM_SIZE)
int          i,j, nbytes;
int64_t      tm0,tm1,indx;
int          varx,vara,varb,varc,prod3,prod2,prod1,fx;
int          xg,ag,bg,cg;

/*****
*   Read into OBM. Cooeff & segment endpoints *
*****/

// 4 data values (seg,a,b,c), 64bit Hex values
nbytes = 4*ncoef * 8;
DMA_CPU   (CM2OBM,   segend,   MAP_OBM_stripe(1,"A,B,C,D"),   ac,   1,
nbytes, 0);
wait_DMA (0);

// Read in the Number of points
nbytes = xpts * 8;
DMA_CPU (CM2OBM, x, MAP_OBM_stripe(1,"E"), xc, 1, nbytes, 0);
wait_DMA (0);

// DEBUG: Tell me I'm in the MAP
printf ("\n\n***** NOW IN MAP *****\n");
printf ("MAP subr ncoef %i xpts %i \n",ncoef,xpts);

/*****
*   Read timer and use selector to determine the segment *
*****/
read_timer (&tm0);
for (i=0;i<xpts;i++)
{

    split_64to32(x[i],&xg,&varx);

    // SEGMENT INDEX ENCODER
    // Based on x input, determine which index to select
    // the coefficients for approximation

    select_pri_32bit_16val( varx<=  0x12de,  0,
                           varx<=  0x2087,  1,
                           varx<=  0x2c8c,  2,
                           varx<=  0x37a9,  3,
                           varx<=  0x422b,  4,
                           varx<=  0x4c45,  5,
                           varx<=  0x5613,  6,
                           varx<=  0x5faa,  7,
                           varx<=  0x6916,  8,
                           varx<=  0x7268,  9,
                           varx<=  0x7bac, 10,
                           varx<=  0x7fff, 11,
                           varx<=  0x7fff, 11,
                           varx<=  0x7fff, 11,
                           varx<=  0x7fff, 11,
                           11, &indx);

```

```

        indx = i%12;
        split_64to32(a[indx],&ag,&vara);
        split_64to32(b[indx],&bg,&varb);
        split_64to32(c[indx],&cg,&varc);

        // use macro multiplier
        my_mult(varx,varx,&prod1); // prod1 = x^2 term

        // Perform together
        my_mult(prod1,vara,&prod2); // prod2 = ax^2 term
        my_mult(varx, varb,&prod3); // prod3 = bx term

        // Perform final add stage
        //my_add(prod2,prod3,varc,&fx); // 3 input macro adder
        fx = prod2+prod3+varc;

        // Perform final add stage
        // Put result in OBM
        y[i] = fx & 0x00000000FFFFFFFF;

        // DEBUG: printf for debug information on variable status
        //printf ("indx: %3i a[]: %llx varb: %x c: %x x: %x fx: %lx,
y[]: %llx\n",
        //          indx,a[indx],varb,varc,varx,fx,y[i]);
        // printf ("indx: %3i a: %x b: %x c: %x x: %x fx: %lx, y[]:
%llx\n",
        //          indx,vara,varb,varc,varx,fx,y[i]);
        // printf ("prod1: %x prod2: %x prod3: %x \n",
        //          prod1, prod2, prod3);

    } // End for(i=0;i<xpts;i++)

    read_timer (&tml);
    *time0 = tml-tm0;

    /*****
    * Send back the results
    *****/
    nbytes = xpts * 8;
    DMA_CPU (OBM2CM, y, MAP_OBM_stripe(1,"F"), yc, 1, nbytes, 0);
    wait_DMA (0);
}

```

c. *blk.v*

```

module mult_32to32(a, b, clk, prod) /* synthesis syn_black_box */ ;
    input  [31:0] a;
    input  [31:0] b;
    output [31:0] prod;
    input  clk;
endmodule

module add_32(a, b, c, sum) /* synthesis adderparthere */ ;
    input  [31:0] a;

```

```

    input  [31:0] b;
    input  [31:0] c;
    output [31:0] sum;
endmodule

```

d. info

```

BEGIN_DEF "my_mult"
    MACRO      = "mult_32to32";
    STATEFUL   = NO;
    EXTERNAL   = NO;
    PIPELINED  = YES;
    LATENCY    = 7;
    INPUTS     = 2:
        I0 = INT 32 BITS (a) // explicit input
        I1 = INT 32 BITS (b) // explicit input
        ;
    OUTPUTS    = 1:
        O0 = INT 32 BITS (prod) // explicit output
        ;

    IN_SIGNAL : 1 BITS "clk" = "CLOCK";

    DEBUG_HEADER = #
        void my_mult__dbg (int a, int b, int *prod);
    #;

    DEBUG_FUNC = #
        void my_mult__dbg (int a, int b, int *prod){
            *prod = a*b;
            *prod >>= 32;
        }
    #;
END_DEF

BEGIN_DEF "my_add"
    MACRO      = "add_32";
    STATEFUL   = NO;
    EXTERNAL   = NO;
    PIPELINED  = NO;
    LATENCY    = 1;
    INPUTS     = 3:
        I0 = INT 32 BITS (a) // explicit input
        I1 = INT 32 BITS (b) // explicit input
        I2 = INT 32 BITS (c) // explicit input
        ;
    OUTPUTS    = 1:
        O0 = INT 32 BITS (sum) // explicit output
        ;

    DEBUG_HEADER = #
        void my_add__dbg (int a, int b, int c, int *sum);
    #;

```

```
DEBUG_FUNC = #  
    void my_add__dbg (int a, int b, int c, int *sum){  
        *sum = a+b+c;  
    }  
#;  
END_DEF
```

APPENDIX D. COPY OF PROFILE REPORT

The profile report shows the execution time for non-uniform segmentation with the following parameters: $\sqrt{-\ln(x)}$, $\varepsilon = 2^{-33}$ and $N = 1,000,000$. Profile reports are used to debug functions, optimize files and understand the dynamics and choke points in the program. Parent functions and child functions can be analyzed to find the slow points in the program.

The longest times in the report, 62.906s and 50.703s belong to *xlabel* and *ylabel*, respectively. They were used to display graphs for debugging purposes. Any function used to drive graphics is slow compared to computation. In a final version, the display is not required and these times do not exist and therefore have no impact.

The next longest functions are 29.063 seconds and 26.359 seconds which correspond to *multipleQuadApprox* and *varQuadApproxHybThirdNew* respectively. However notice that these are total times. *multipleQuadApprox* is a parent function to *varQuadApproxHybThirdNew*. Notice too that the column *Self Time* indicates the amount of time that the function actually spends in itself, i.e. the remaining time is spent in the child functions. The child function to *varQuadApproxHybThirdNew* is *chebyRemez*. This makes *chebyRemez* the longest part of the code. The child functions in *chebyRemez* take up a lot of time, but *chebyRemez* is the most suitable metric for comparing the speed of the different functions.

Profile Summary

Generated 28-Jul-2007 08:59:56

Function name	Calls	Total Time	Self Time*
UserInput	1	0.094 s	0.094 s
ancestor	5252	1.141 s	function is recursive
ancestor>isatype	10504	0.469 s	function is recursive
axes (Opaque-function)	5252	0.141 s	0.141 s

axescheck	18356	0.859 s	0.859 s
cell.intersect	3	0.016 s	0.000 s
cell.setdiff	3	0 s	0.000 s
cell.sort	15	0.016 s	0.016 s
cell.strmatch	1	0 s	0.000 s
cell.unique	9	0.016 s	0.000 s
cellfun (MEX-function)	49	0 s	0.000 s
cellstr	6	0 s	0.000 s
chebyRemz	4182	20.469 s	11.328 s
colstyle	1	0 s	0.000 s
deal	1	0 s	0.000 s
double.superiorfloat	34078	0.141 s	0.141 s
fcnchk	1	0 s	0.000 s
findall	2	0 s	0.000 s
fliplr	35592	0.391 s	0.391 s
gca	13113	0.922 s	0.578 s
gcf	13113	0.391 s	0.391 s
getF	1	0.094 s	0.078 s
getappdata	6	0 s	0.000 s
graph2d.series.schema>LdoDirtyAction	3	0.016 s	function is recursive
...h2d.series.schema>LdoModeSwitchAction	2	0 s	function is recursive
...series.schema>LdoSetManualModeAction	1	0 s	function is recursive
graph2d.series.schema>LdoYDataAction	1	0 s	function is recursive
graph2d.series.schema>LsetXDataSilently	1	0 s	0.000 s
graphics\private\clo	2	0.031 s	0.000 s
graphics\private\clo>find_kids	2	0 s	0.000 s

handle.listener (Opaque-function)	6	0 s	0.000 s
hasbehavior	2	0 s	0.000 s
hold	2623	1.422 s	0.438 s
inline.feval	164	0.031 s	0.016 s
inline.inline	3	0.094 s	0.000 s
inline.inline>strtrim	3	0 s	0.000 s
inline.subsref	46123	12.172 s	1.563 s
inlineeval	46287	10.625 s	10.625 s
int2str	2622	0.219 s	0.219 s
intersect	3	0.016 s	0.016 s
isappdata	7871	0.563 s	0.344 s
iscell	9	0 s	0.000 s
iscellstr	41	0 s	0.000 s
isfield	7877	0.219 s	0.219 s
ishghandle	5252	0.250 s	0.250 s
ishold	1	0 s	0.000 s
iskeyword	2636	0.078 s	0.078 s
ismembc (MEX-function)	1	0 s	0.000 s
ismembc2 (MEX-function)	1	0 s	0.000 s
ismember	8	0 s	0.000 s
isobject	1	0 s	0.000 s
ispc	6	0 s	0.000 s
isstruct	1	0 s	0.000 s
isvarname	2638	0.188 s	0.109 s
legend	1	0.016 s	function is recursive
legend>find legend	1	0 s	function is recursive

legend>islegend	1	0 s	0.000 s
legendinfo	1	0.016 s	function is recursive
legendinfo>check_xydata	3	0 s	0.000 s
legendinfo>parsestruct	2	0 s	function is recursive
line (Opaque-function)	3	0 s	0.000 s
linspace	4183	0.391 s	0.391 s
log10	2622	0.016 s	0.016 s
maple	36	0 s	0.000 s
maplemex (MEX-function)	36	0 s	0.000 s
meshgrid	4	0 s	0.000 s
multipleQuadApprox	1	29.063 s	0.188 s
newplot	2624	1.453 s	0.500 s
newplot>ObserveAxesNextPlot	2624	0.641 s	0.047 s
newplot>ObserveFigureNextPlot	2624	0.094 s	0.094 s
num2str	5244	0.828 s	0.594 s
opaque.double	11	0 s	0.000 s
parseparams	1	0 s	0.000 s
plotdoneevent	1	0 s	0.000 s
polyval	34078	1.922 s	1.781 s
quadl	1	0.078 s	0.000 s
quadl>quadlstep	163	0.078 s	function is recursive
scribe.legendinfo (Opaque-function)	4	0 s	function is recursive
scribe.legendinfo.legendinfo	1	0 s	function is recursive
scribe.legendinfochild (Opaque-function)	12	0 s	function is recursive
scribe.legendinfochild.legendinfochild	3	0 s	function is recursive
setdiff	7	0.078 s	0.063 s

sortcellchar (MEX-function)	15	0 s	0.000 s
specgraph.baseline (Opaque-function)	7	0.047 s	function is recursive
specgraph.baseline.baseline	1	0.047 s	function is recursive
specgraph.stemseries (Opaque-function)	25	0.078 s	function is recursive
specgraph.stemseries.refresh	2	0.016 s	function is recursive
...stemseries.schema>LdoEdgeColorAction	1	0 s	0.000 s
...stemseries.schema>LdoFaceColorAction	1	0 s	0.000 s
...ies.schema>LdoSetManualCodeModeAction	3	0 s	function is recursive
...aph.stemseries.schema>LdoUpdateAction	2	0 s	0.000 s
...series.schema>LdoUpdateBaselineAction	1	0 s	0.000 s
...ies.schema>LdoUpdateChildMarkerAction	2	0 s	0.000 s
...series.schema>LdoUpdateChildrenAction	3	0.016 s	function is recursive
...temseries.schema>LdoUpdateXDataAction	2	0 s	0.000 s
specgraph.stemseries.setLegendInfo	1	0.016 s	function is recursive
specgraph.stemseries.stemseries	1	0.063 s	function is recursive
specgraph\private\checkvpairs	1	0 s	0.000 s
specgraph\private\nextstyle	1	0.016 s	0.016 s
stem	1	0.109 s	0.016 s
stem>parseargs	1	0 s	0.000 s
str2num	10	0.016 s	0.016 s
str2num>protected_conversion	10	0 s	0.000 s
strmatch	1	0 s	0.000 s
sym.abs	1	0 s	0.000 s
sym.char	16	0.016 s	0.016 s
sym.diff	3	0.016 s	0.000 s
sym.eq	1	0 s	0.000 s

sym.findsym	3	0.016 s	0.000 s
sym.findsym>pickvar	3	0.016 s	0.016 s
sym.log	2	0.047 s	0.000 s
sym.maple	10	0.047 s	0.000 s
sym.sqrt	2	0.016 s	0.016 s
sym.sym	1329	0.266 s	0.063 s
sym.sym>char2sym	1324	0.203 s	0.094 s
sym.sym>trim	1324	0.031 s	0.000 s
sym.uminus	2	0 s	0.000 s
syms	1314	0.578 s	0.219 s
symvar	3	0.094 s	0.000 s
symvar>findrun	12	0.016 s	0.016 s
symvar>isquoted	3	0 s	0.000 s
title	5244	1.234 s	function is recursive
unique	4	0.016 s	0.016 s
usev6plotapi	1	0 s	0.000 s
varQuadApproxHybThirdNew	1311	26.359 s	3.297 s
vectorize	3	0.031 s	0.031 s
xlabel	5244	62.906 s	function is recursive
xychk	1	0 s	0.000 s
ylabel	5244	50.703 s	function is recursive

Self time is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling.

APPENDIX E. LESSONS LEARNED

This section provides information and a record of problems that were encountered while using the SRC-6, and other software applications in this thesis. The intent is to provide a reference to specific issues previously encountered and to reduce the amount of time to resolve or understand them in the future.

E.1 FILE NAMING PROBLEMS

Problem: When you compile your VHDL code using Xilinx's ISE Navigator, it accepts upper and lower case versions of letters as the same. That is, `adderVerilog.vhd` and `adderverilog.vhd` are the same file to Xilinx's ISE Navigator. However, files in the SRC are case sensitive. That is, `adderVerilog.vhd` and `adderverilog.vhd` are DIFFERENT files in the SRC-6. So, if you have listed `adderverilog.vhd` in your Makefile as a macro, it will not recognize `adderVerilog.vhd` as the target file. Additionally, if you let Xilinx create VHDL code from a schematic which contains the module `adderVerilog.vhd` it will list refer to the module in the VHDL code as `adderverilog.vhd`.

Solution: Use lower case letters for ALL files.

Author: J.T. Butler

Date: 26 FEB 07

E.2 USING THE CONST CONSTRUCT IN C

Problem: A `martello64` error is obtained when using

```
int64_t array[5][5] = { {1,2,3,4,5};
                        {6,7,8,9,10};
                        {11,12,13,14,15};
                        {16,17,18,19,20};
                        {21,22,23,24,25} };
```

The error is caused by "too many accesses to BRAM".

Background: This is a correct C construct when used on a PC or workstation. However, when it is in a `.mc` file, this declaration will cause a `martello64` error. It is possibly due to too many accesses to a BRAM (arrays are usually stored in BRAM).

This was a problem that Scott Bailey experienced. The initial writeup is based on a conversation between Scott Bailey and Jon Butler on December 1, 2006

Solution: In discussing this with Dave Caliga, Scott learned that the Carte™ 2.2 version should correct this error. At the time the error occurred, we were using Carte™ 2.1. Apparently, Carte™ 2.2 spaces out the accesses to BRAM so that it can be changed to include ALL 25 data values. However, in order to use it in Carte™ 2.2, you need to declare the array as a constant, like so

```
const int64_t array[5][5] = { {1,2,3,4,5};
                              {6,7,8,9,10};
                              {11,12,13,14,15};
                              {16,17,18,19,20};
                              {21,22,23,24,25} }
```

The intent of `const` is to set up a constant array that is not changed in the rest of the program, much like a ROM instead of RAM.

Scott Bailey tried to work around this error by simply defining the array without populating it with initial values, using, for example: `int64_t array[5][5];` The compiler accepted this. He then put the desired values into `array` using `for` loops. These arrays will then work as normal C arrays within the `.mc` code. However, this decreases performance, since the values placed into the array must come from either OBM or streams, access of which will incur a time penalty. Scott believes that the problem is in putting too many values into BRAM too quickly. In a dialog with Dave Caliga (SRC Computers), Dave said that the problem occurs when there are more than 8 initialized values placed in the array. Scott believes that this problem will occur in BOTH Carte™ 2.1 and 2.2 for non-constant BRAM arrays.

Author: J.T. Butler
Date: 26 FEB 07

E.3 INCORRECT ARGUMENTS IN SYSTEM SUPPLIED MACROS

Problem: A core dump occurs when the call-by-value and call-by-reference conventions are not adhered to

```
popcount_64(int64_t a, int array[i])
```

Instead of an error message, there will be a core dump.

Background: This was provided by Scott Bailey in a conversation with Jon Butler on December 1, 2006.

Solution: To solve this problem, use the following code.

```
popcount_64(int64_t a, &temp)
array[i] = temp;
```

For most system macros, SRC requires that the input values be passed as call-by-value (e.g. a) and all output values be done as call-by-reference (e.g. &temp).

Author: J.T. Butler

Date: 26 FEB 07

E.4 IF / THEN / ELSE LIMITATION

Problem: When programming in C within the .mc file (no macro) an error occurs when the “If, then, else” chain is too long (approx 26 long).

Background: This was discovered by Prof. Jon Butler when trying to implement a long “if,then,else” string during testing.

Solution: SRC Carte™ V2.2 fixes this problem.

Author: T.J. Mack

Date: 26 FEB 07

E.5 MULTIPLE FILES USED IN A MACRO

Problem: When using multiple files to describe a circuit in a macro, the SRC won’t successfully compile.

Background: This was discovered while developing the NFG macro where different modules are described in separate VHDL files.

Solution: List all of the VHDL files within the *Makefile* under macros, separated by a space.

Author: T.J. Mack

Date: 26 FEB 07

E.6 XILINX / SYNPLIFY INCONSISTENCIES

Problem: VHDL code synthesizes correctly (no errors) in Xilinx XST, but does not in Synplify PRO.

Background: When developing VHDL code for the NFG, the code was originally written in the Xilinx ISE. Checking for errors using Xilinx XST resulted in no errors. When the code was transported to the SRC, errors resulted. Further troubleshooting produced the same errors when using the stand-alone Synplify.

Solution: Not all code is universal. Always test code using a stand-alone version of Synplify. If it results in errors, the code must be modified.

Author: T.J. Mack

Date: 26 FEB 07

E.7 MODELSIM AND MULTIPLE HDL'S

Problem: ModelSim XE (Xilinx Edition) which is obtained for free from the Xilinx website does not support multiple HDL's.

Background: When developing the NFG, some code was provided by SRC in Verilog. When attempting to analyze the circuit with a test bench, an error occurred in ModelSim. The error stated that ModelSim XE does not support multiple HDL's.

Solution: Download ModelSim SE. NPS has a license. Details available from Dan Zulaica.

Author: T.J. Mack

Date: 26 FEB 07

E.8 INITIALIZING MEMORY FROM A SEPARATE FILE

Problem: Xilinx allows one to synthesize a ROM where the ROM contents are specified in a separate file. When transferring the VHDL files to the SRC and synthesizing with Synplify, an error results. This is another artifact of problem F. above.

Background: Because of the potentially large amount of data needed to load into a ROM, it is useful to have a separate file with just this data. The HDL must then access this data file during synthesis.

Solution: Problem not completely solved, yet. Some potential solutions are:

1. Below is a ROM provided by SRC Computers. Written in Verilog, (SRC Computer's preferred language) it is comprised of 32, 4-input, 1-bit output LUTs. It has a 32-bit output. It is initialized using a separate *.sdc* file.

```
module MY_ROM (
    data,
    adr
);
    output [31:0] data;
    input [3:0] adr;

    ROM16X1 M0 (
        .O      (data[0]),
        .A0      (adr[0]),
        .A1      (adr[1]),
        .A2      (adr[2]),
        .A3      (adr[3])
    );

    ROM16X1 M1 (
        .O      (data[1]),
        .A0      (adr[0]),
        .A1      (adr[1]),
        .A2      (adr[2]),
```

```

        .A3      (adr[3])
    );

    ...

***      Fill-In Remaining Modules      ***

    ...

ROM16X1 M31 (
    .O      (data[31]),
    .A0      (adr[0]),
    .A1      (adr[1]),
    .A2      (adr[2]),
    .A3      (adr[3])
);

endmodule

```

The ROM initialization values are in the *.sdc* file below. The INITs are somewhat cumbersome, since the LUTs are 1-bit wide. So each of the LUTs has one bit position for all of the 16 values. The INIT values essentially represent a 32 row by 16 column matrix. Each column represents one of 16, 32-bit outputs.

```

define_attribute {i:M0} xc_props "INIT=ba5d"
define_attribute {i:M1} xc_props "INIT=8801"

    ...

***      Fill-In Missing Values      ***

    ...

define_attribute {i:M31} xc_props "INIT=1321"

```

This is the most promising example of a ROM with an external file for initialization. However, the 1-bit format of the init values makes it difficult to implement.

2. Below is another ROM example provided by SRC Computers. It uses the RAMB16_S18_S18 module which is a 16 Kb Block RAM with two 18-bit outputs (16-bits plus 2-bits for parity). It is initialized using the xc_props lines within the same file.

```

module MY_ROM (
    din_0,
    dout_0,
    din_1,
    dout_1,
    adr_0,
    adr_1,
    w_en_0,
    w_en_1,
    clk
);
    input [15:0] din_0;
    output [15:0] dout_0;
    input [15:0] din_1;
    output [15:0] dout_1;
    input [9:0] adr_0;
    input [9:0] adr_1;
    input w_en_0;
    input w_en_1;
    input clk /* synthesis syn_noclockbuf=1 */ ;

```



```

RAMB16_S18_S18 M0 (
    .DOA      (dout_0[15:0]),
    .DOB      (dout_1[15:0]),
    .DOPA     (),          // ignore the parity outputs
    .DOPB     (),          // ignore the parity outputs
    .ADDRA    (adr_0),
    .ADDRB    (adr_1),
    .CLKA     (clk),
    .CLKB     (clk),
    .DIA      (din_0[15:0]),
    .DIB      (din_1[15:0]),
    .DIPA     (2'b0),      // zero the parity inputs
    .DIPB     (2'b0),      // zero the parity inputs
    .ENA      (1'b1),
    .ENB      (1'b1),
    .SSRA     (1'b0),
    .SSRB     (1'b0),
    .WEA      (w_en_0),
    .WEB      (w_en_1)
) /* synthesis

xc_props="INIT_00=76931fac9dab2b36c248b87d6ae33f9a62d7183a5d5789e4b2d6b441e2411dc7,\
INIT_01=09e111c7e1e7acb6f8cac0bb2fc4c8bc2ae3baaab9165cc458e199cb89f51b13,\
INIT_02=5f7091a5abb0874df3e8cb4543a5eb93b0441e9ca4c2b0fb3d30875cbf29abd5,\
INIT_3e=1a0bf9b00ffd21b6210b11dc59ec947be86d11e10de2e980b8bc988e26aba269,\
    . . .
***      Fill-In Missing Values      ***
    . . .
INIT_3f=ac6bd4cd2bf0471ffcb95377922449de5393850a00a57b47800d374d961dfef5" */ ;

endmodule

```

3. The following code is a 16 x 32-bit ROM written in Verilog. It will synthesize in Xilinx XST, but not in Synplify PRO.

```

module romverlog(input [3:0] raddr, output [31:0] slope_int);

reg [15:0] mem [31:0];

initial
begin
    $readmemb("memory.mem", mem);
end

    assign slope_int = mem[raddr];

endmodule

```

The associated *memory.mem* file is a simple, binary text file with the memory initialization values.

```

0000011001000100000000000000000000
0000011000101101000000000000000000
000001011111111100000000000000100
000001011011101000000000000001100
000001010110000000000000000011010
000001001111000100000000000101111
00000100011100000000000001001101
00000011110111110000000001110100

```

```
000000110011111110000000010100101
00000010100100110000000011100001
00000001110111100000000100100111
00000001001000010000000101110111
00000000011000000000000111001111
00000001110111100000000100100111
00000001001000010000000101110111
00000000011000000000000111001111
```

Author: T.J. Mack
Date: 26 FEB 07

E.9 MACRO LATENCY AND SRC OVERHEAD

Problem: When implementing a macro, SRC requires additional clocks to accomplish *overhead* operations. The overhead appears to be 5 clock cycles to pass data *to* a macro and an additional 5 clock cycles to receive data *from* a macro. One would expect a macro with a latency of 3 to take a total of 13 clock cycles. However, it takes only 12. The last clock cycle is absorbed into the 5 clock cycles needed to receive data from the macro. In this case, the *latency* in the *info* file must be set equal to 2, even though the schematic may show a latency of 3.

Background: When developing the NFG, *pipeline depth* reports for the loop that calls the NFG macro were always 10 clock cycles more.

Solution: No solution. This is a characteristic of the SRC architecture.

Author: T.J. Mack
Date: 26 FEB 07

E.10 CANNOT USE PRIORITY SELECTOR GREATER THAN 128

Problem: When implementing a priority selector with 256 elements, 64 bits wide, I could not compile the *.mc* file. This is because the architecture already had 3 64 bit wide multipliers and other hardware that consumed some of the resources. However, if you don't need all 256 priority selectors, it would be nice to have a selector that is greater than 128, and smaller than 256.

Background: When implementing the priority selectors with 150 elements, the only option for a single selector is to use the 256 selector, but that is 106 more elements than required.

Solution: Use multiple selectors of smaller sizes.

Author: N. Macaria
Date: 26JUL07

E.11 IF-THEN-ELSE STATEMENT WITH SRC PRIORITY SELECTORS

Problem: When implementing multiple priority selectors in the *.mc* file, SRC would not accept an if-then-else statement to contain priority selectors in the body.

Background: When running the program, it would not compile if a priority selector was used inside an if-then-else statement..

Solution: Put the if-then-else statement prior to the priority selector, use a variable to store the selector you want to pick, then use a case statement to reach that selector.

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Date: 26JUL07

E.12 FIND THE SLOW CODE IN MATLAB PROGRAMS

Problem: When running MATLAB programs, sometimes the code takes very long to execute and you may not be sure where the problem exists.

Background: When running the *chebyRemz*, program, there were portions of code that would take very long to run.

Solution: Put the if-then-else statement prior to the priority selector, use a variable to store the selector you want to pick, then use a case statement to reach that selector.

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Date: 26JUL07

APPENDIX F. SEGMENT ESTIMATION EQUATION

The segment estimation equation is derived from analyzing the *Chebyshev* approximation error equation (0.6) is the general case:

$$\varepsilon = \frac{2(b-a)^{d+1}}{4^{d+1}(d+1)!} \left| f_{\max}^{d+1}(x) \right| \quad (0.6)$$

The variable d is the order of the approximation to be used. For the case of quadratic approximation, $d=2$ and $(b-a)$ is the estimated width of the segment.

$$\varepsilon = \frac{2(b-a)^3}{4^3(3)!} \left| f_{\max}^{\text{III}}(x) \right|$$

$$\frac{(4^3 \times 3 \times 2) \varepsilon}{2 \times \left| f_{\max}^{\text{III}}(x) \right|} = (b-a)^3$$

$$(b-a)^3 = \frac{(4^3 \times 3 \times 2) \varepsilon}{2 \times \left| f_{\max}^{\text{III}}(x) \right|} = (4^3) \times \frac{3\varepsilon}{\left| f_{\max}^{\text{III}}(x) \right|}$$

$$(b-a) = \sqrt[3]{(4^3) \times \frac{3\varepsilon}{\left| f_{\max}^{\text{III}}(x) \right|}}$$

$$EstLenSeg = (b-a) = 4 \times \left[\frac{3 \times \varepsilon}{\left| f_{\max}^{\text{III}}(x) \right|} \right]^{\frac{1}{3}} \quad (0.3)$$

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